

(NASA-CR-120226) MEASUREMENT COMPONENT
TECHNOLOGY. VOLUME 1: CRYOGENIC
PRESSURE MEASUREMENT TECHNOLOGY, HIGH
PRESSURE FLANGE SEALS, (North American
Rockwell Corp.)

N74-27185

Unclas
40512

SD 72-SA-0156-1

Measurement Component Technology

Cryogenic Pressure Measurement Technology,
High Pressure Flange Seals, Hydrogen Embrittlement
of Pressure Transducer Material, Close Coupled Vs.
Remote Transducer Installation And Temperature
Compensation of Pressure Transducers.

Final Report

13 October 1972

Volume I

Contract NAS7-200

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REPRODUCED BY
**NATIONAL TECHNICAL
INFORMATION SERVICE**
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161



Space Division
North American Rockwell

TECHNICAL REPORT INDEX/ABSTRACT

ACCESSION NUMBER				DOCUMENT SECURITY CLASSIFICATION UNCLASSIFIED			
TITLE OF DOCUMENT MEASUREMENT COMPONENT TECHNOLOGY, CRYOGENIC PRESSURE MEASUREMENT TECHNOLOGY, HIGH PRESSURE FLANGE SEALS, HYDROGEN EMBRITTLE- MENT OF PRESSURE TRANSDUCER MATERIAL, CLOSE COUPLED VS. REMOTE TRANS- DUCER INSTALLATION AND TEMPERATURE COMPENSATION OF PRESSURE TRANSDUCERS							LIBRARY USE ONLY
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CODE QNO852 85282		ORIGINATING AGENCY AND OTHER SOURCES SPACE DIVISION, NORTH AMERICAN ROCKWELL CORPORATION DOWNEY, CALIFORNIA				DOCUMENT NUMBER SD 72-SA-0156-1	
PUBLICATION DATE OCTOBER 13, 1972				CONTRACT NUMBER NAS7-200			
DESCRIPTIVE TERMS TRANSDUCERS FLOWMETERS PRESSURE TRANSDUCERS STRAIN GAGES FLANGE SEALS HYDROGEN EMBRITTLEMENT TEMPERATURE TRANSDUCERS							
ABSTRACT THIS REPORT DOCUMENTS THE RESULTS OF AN INVESTIGATION INTO THE AVAILABILITY AND PERFORMANCE CAPABILITY OF MEASUREMENT COMPONENTS IN THE AREA OF CRYOGENIC TEMPERATURE, PRESSURE, FLOW AND LIQUID DETECTION COMPONENTS AND HIGH TEMPERATURE STRAIN GAGES. IN ADDITION, TECHNICAL SUBJECTS ALLIED TO THE COMPONENTS WERE RESEARCHED AND DISCUSSED. THESE SELECTED AREAS OF INVESTIGATION WERE: (1) HIGH PRESSURE FLANGE SEALS, (2) HYDROGEN EMBRITTLEMENT OF PRESSURE TRANSDUCER DIAPHRAGMS, (3) THE EFFECTS OF CLOSE-COUPLED VERSUS REMOTE TRANSDUCER INSTALLATION ON PRESSURE MEASUREMENT, (4) TEMPERATURE TRANSDUCER CONFIGURATION EFFECTS ON MEASUREMENTS, AND (5) TECHNIQUES IN TEMPERATURE COMPENSATION OF STRAIN GAGE PRESSURE TRANSDUCERS. THE PURPOSE OF THE PROGRAM WAS TO INVESTIGATE THE LATEST DESIGN AND APPLICATION TECHNIQUES IN MEASUREMENT COMPONENT TECHNOLOGY AND TO DOCUMENT THIS INFORMATION ALONG WITH RECOMMENDATIONS FOR UPGRADING MEASUREMENT COMPONENT DESIGNS FOR FUTURE S-II DERIVATIVE APPLICATIONS. RECOMMENDATIONS ARE PROVIDED FOR UPGRADING EXISTING STATE-OF-THE-ART IN COMPONENT DESIGN, WHERE REQUIRED, TO SATISFY PERFORMANCE REQUIREMENTS OF S-II DERIVATIVE VEHICLES.							

FOREWORD

This report documents the work performed by North American Rockwell Corporation through its Space Division in fulfillment of a Task Authorization entitled, "Measurement Component Technology," sponsored by the National Aeronautics and Space Administration's George C. Marshall Space Flight Center, Huntsville, Alabama, under contract NAS7-200 in accordance with Task Authorization 2026-TA-36. The work was performed by members of the Electrical and Electronics Systems branch of the Space Systems and Applications Division during the period July 12, 1971 through October 13, 1972. NASA technical monitors were Messrs. W. T. Escue, S&E-ASTR-III, H. S. Herman and R. C. Holder, S&E-ASTR-IMP, J. F. Hamlet, S&E-ASTR-IMF and J. E. Zimmerman, S&E-ASTR-IMT.

The report consists of three volumes, of which this is Volume I. Volume numbers, document numbers and volume titles are listed below.

- Volume I - Cryogenic Pressure Measurement Technology and Subjects Allied to Pressure Transducers. Document Number SD72-SA-0156-1.
- Volume II - Liquid Detection Measurement Technology and Cryogenic Flow Measurement Technology. Document Number SD72-SA-0156-2.
- Volume III - Cryogenic Temperature Measurement Technology and High Temperature Strain Gage Technology. Document Number SD72-SA-0156-3.

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ACKNOWLEDGEMENTS

The authors are indebted to the many companies and Government Agencies listed below who have contributed information and assistance during the preparation of this report. Also, acknowledgements are made to the many authors whose publications, which are referenced in the Bibliography, have been used as reference sources for information contained in this report.

Acoustica Associates
Automation Industries, Inc.
Avien, Inc., Instrumentation Division
Bell & Howell/Consolidated Electrodynamics
Bendix Corporation
BLH Electronics, Inc.
Bourns, Inc.
Conrac, Avionics Sales Division
Consolidated Controls
Cox Instrumentation
Delaware Manufacturing Co.
Dentronics, Inc.
Dynasciences Corporation
Eastech, Incorporated
Electro Development Corporation
Fisher and Porter
Flow Technology, Incorporated
Foxboro Instruments
General Electric Company
Genisco Technology Corporation
Hastings-Raydist
Honeywell, Incorporated
Hy-Cal Engineering
Industrial Nucleonics Corp.
ITT Barton
Kistler Instrument Corporation
Liquid Meter Corporation
MB Electronics
Microdot, Inc., Instrumentation Division
Micro-Measurements
National Bureau of Standards (Boulder, Colorado)
Product Specialist - Metal V-Seal Parker Seal Co.
Quantum Dynamics, Incorporated
RdF Corporation
Revere Corporation
Rosenount Engineering
Servo Mechanism
Simmonds Precision Products, Inc.
Stetham Instruments, Inc.
Thermo-Systems, Incorporated
Trans-Sonics, Inc.
Tyco Laboratories
United Controls
Victory Engineering
Vinson Manufacturing Company
Wyle Laboratories



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ACKNOWLEDGEMENTS

The work performed in this study was accomplished by a team under the direction of Study Manager K. K. Hayakawa. R. M. Chrisco performed the investigation into hydrogen embrittlement of pressure transducer materials. C. S. Greenough conducted the research into high pressure flange sealing. M. M. Iwata investigated bridge designs for platinum wire thermometry. C. F. Lytle investigated cryogenic liquid detection and temperature transducers. D. R. Udell conducted the study into cryogenic flowmeters, close-coupled versus remotely installed pressure transducers and temperature compensation designs for strain gage pressure transducers. J. A. Walling performed the investigation into high temperature strain gages.

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DEFINITION OF TERMS AND ABBREVIATIONS

LOX	-	Liquid oxygen
LH ₂	-	Liquid hydrogen
SPS	-	Samples per second
FSO	-	Full scale output
FS	-	Full scale
FR	-	Full range
Split package	-	Refers to a transducer where the sensor and its associated electronics are contained in two separate modules

1.0 INTRODUCTION

As space missions become more complex and more demanding, the requirements on measurements grow more and more difficult. Constant improvements in measurement techniques and accuracy are being sought by design engineers for a more accurate evaluation of system performances. Ever increasing severity in operating environments requires a continued search for new designs and techniques.

Greater reliability of equipment is required as space missions grow more complex. Lower component weight, smaller size and lower electrical power consumption are sought as mission duration grows longer. All of these factors and many more require that measurement capabilities be upgraded to meet these new demands. The purpose of this study is to satisfy some aspects of this need with an investigation into measurement component technology.

S-II derivative systems, including the Space Tug, Orbiting Propellant Depot (OPD), Expendable Second Stage (ESS), and Chemical Interorbital Shuttle (CIS) impose many new performance requirements on measurement components not currently required by the S-II stage or the Saturn V vehicle.

Higher measurement accuracy, long term operation in high and low temperature environments, repeated operations in relatively high vibration environments, long term shelf life and repeated reuses are some of the more important performance requirements. Light weight, small package size, simplified wiring requirements, low electrical power, and simplified maintenance procedures are other desirable characteristics for future space vehicles.

This program investigated the availability and performance capability of specific measurement components in the area of cryogenic temperature, pressure, flow and liquid detection components and high temperature strain gages. The study conducted a systematic survey of manufacturers to establish performance and physical characteristics of current designs. In cases where current state-of-the-art equipment cannot meet performance requirements for future space missions, the design shortcomings are identified and recommendations for improvements, where available, were presented and discussed. The study evaluated published information and supplier furnished data and discussed some advantages and disadvantages for given designs. Measurement system application design considerations were investigated and discussed in the report where these considerations were an important part of the measurement. The results of the investigation were intended to provide a useful reference source for design and component information for the selection and application of the measurement transducers of this investigation.

In addition, specific technical topics allied to the measurement type or components were researched and are discussed in this report. Items selected for investigation as part of this study were selected for the problem nature of the item or for the technical value of the researched information as a reference source for new designs. Selected areas for investigation were (1) high pressure flange seals, and (2) hydrogen embrittlement of pressure



transducer materials. Other topics which involve application were (1) the effects of close-coupled versus remote transducer installation on pressure measurements, (2) temperature transducer configuration effects on measurements, and (3) techniques in temperature compensation of close-coupled strain gage pressure transducers.

These specific measurement component capabilities and technical topics are contained in three volumes. Volume I contains Cryogenic Pressure Measurement Technology, High Pressure Flange Seals, Hydrogen Embrittlement of Pressure Transducer Materials, the Effect of Close-Coupled Versus Remote Transducer Installations on Pressure Measurements, and Techniques in Temperature Compensation of Strain Gage Pressure Transducers. Volume II consists of Cryogenic Flow Measurement Technology and Cryogenic Liquid Detection Measurement Technology. Volume III summarizes Cryogenic Temperature Measurement Technology and High Temperature Strain Gage Technology.

CRYOGENIC PRESSURE MEASUREMENT TECHNOLOGY

The investigation into cryogenic pressure transducer technology was made by conducting a survey of manufacturers to establish transducer capability of currently available equipment. The requirement established for the search was to locate an instrument capable of operating with liquid oxygen or liquid hydrogen systems of a space vehicle while maintaining temperature sensitivity errors within 2 percent of full scale.

Since the investigation did not result in meeting this design goal, a literature research was conducted to identify problem areas which contribute to this transducer performance limitation.

This report presents the results of the industrial survey and the literature research.

HIGH PRESSURE FLANGE SEALS

Consideration of a high pressure (5000 psi) transducer for applications whose design concept utilized flanged mounting precipitated this investigation. The research work primarily addresses itself to the search for a metallic seal to attain optimum sealing for low temperature, high pressure systems. The investigation relied principally upon published literature as the source for information.

HYDROGEN EMBRITTLEMENT OF PRESSURE TRANSDUCER MATERIALS

The hydrogen embrittlement investigation utilized published literature for obtaining information on the susceptibility of transducer materials to the embrittlement problem. The investigation emphasized the practical approach by categorizing transducer metals with respect to embrittlement susceptibility. The investigation did not deal with the atomic structure or metallurgical aspects of metals.

THE EFFECTS OF CLOSE-COUPLED VERSUS REMOTE TRANSDUCER INSTALLATION ON PRESSURE MEASUREMENTS

A technical discussion on the effects of close-coupled versus remote transducer installation effects on measurement accuracy was presented in this report for reference information to transducer users. The discussion in the report was based on information derived from Saturn S-II flight tests and laboratory work performed in conjunction with investigations into the Saturn S-II low frequency oscillation phenomenon. Data distortion due to line length is illustrated and corrective methods are delineated.

TECHNIQUES IN TEMPERATURE COMPENSATION OF STRAIN GAGE PRESSURE TRANSDUCERS

Another topic presented in the report is based on investigations of temperature sensitivity problems of strain gage pressure transducers. Since the Saturn S-II low frequency oscillation phenomenon resulted in utilizing close-coupled strain gage transducers on the LOX feedlines of engine 1 and 5, an investigation was made to establish techniques available for compensation of temperature sensitivity errors. This information is provided in this report as reference material.

CRYOGENIC MASS FLOW MEASUREMENT TECHNOLOGY

The flow investigation researched current technology for systems capable of cryogenic temperature flow measurements. Manufacturers were contacted for information on their product line of flowmeters which indicated promise of meeting an application requiring a mass gas flowmeter.

A hypothetical case for a cryogenic temperature gas flow measurement was established for the purpose of assessing whether any of the candidate systems would be acceptable for this case. The report provides the technical discussions resulting from this evaluation as well as descriptions of individual manufacturers systems.

CRYOGENIC LIQUID DETECTION MEASUREMENT TECHNOLOGY

The cryogenic liquid detection technology portion of this study was limited to an industrial survey. Manufacturers of positive and low gravity detection systems were contacted and their equipment and, in some cases, experimental concepts, are presented. The report describes each system including theory of operation, accuracy, stability, power requirements, and the gravitational environment in which the system is designed to perform.

CRYOGENIC TEMPERATURE MEASUREMENT TECHNOLOGY

The investigation into cryogenic temperature transducer technology was made by conducting a survey of manufacturers to establish the capability of currently available equipment to meet cryogenic system requirements. In conjunction with this survey, a literature search was conducted to identify new developments in temperature measuring techniques. The methods of temperature measuring discussed are resistance temperature transducers made from different metals as sensing elements, thermistors, and thermocouples. Also included is a discussion of measuring bridges used to determine the resistance of the temperature probe.



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HIGH TEMPERATURE STRAIN GAGE TECHNOLOGY

Although strain measuring techniques have progressed rapidly since the development of the first strain gage, the requirements for their use have advanced much faster. This is especially true for obtaining flight load measurements on high speed vehicles operating in the earth's atmosphere.

The aerodynamic heat associated with this high speed flight can be a major cause of strain gage error. Temperatures up to 1800 F are anticipated on the aerodynamic surfaces of a mach 6 vehicle operating at 90,000 feet. Strain gage output due to thermal stresses at these high temperatures can produce load measurement errors greater than those due to gage performance characteristics. To obtain accurate flight load measurements these errors must be eliminated in the strain gage design.

The purpose of this section of the components technology report is to review various strain sensing devices and evaluate their performance in a 1500 F to 2000 F thermal environment.



2.0 SUMMARY

The following is a brief review of the significant facts contained in the body of the three volume text. The summary is contained in each of the three volumes in order that the reader might have sufficient information to evaluate his need to review each volume's text in detail.

Volume I contains the following topics: Cryogenic Pressure Transducer Technology, High Pressure Flange Seals, Hydrogen Embrittlement of Transducer Materials, the Effect of Close-Coupled Versus Remote Transducer Installations on Pressure Transducers, and Techniques in Temperature Compensation of Strain Gage Pressure.

Volume II contains the following topics: Cryogenic Mass Flow Measurement Technology and Cryogenic Liquid Detection Technology.

Volume III contains two topics: Cryogenic Temperature Measurement Technology and High Temperature Strain Gage Technology.

CRYOGENIC PRESSURE TRANSDUCER TECHNOLOGY

Pressure measurements for space vehicle cryogenic systems such as for liquid oxygen and liquid hydrogen tanks, transfer lines and engine systems, have always presented a special challenge to instrumentation engineers and measurement users alike. These cryogenic liquids, especially liquid hydrogen, possess many properties which pose problems for designers. Primarily, these problems are associated with low temperature environments and with the highly volatile nature of the liquid. The most common approach to measuring pressure in these systems is to connect the pressure transducer away from the extreme low temperature environment by connecting the transducer to the sense port by a length of sense line which provides a thermal buffer for the transducer. This technique is satisfactory for only steady-state or slowly changing measurements. For oscillating or fast changing pressure systems the volatility of the liquid creates thermal dynamic oscillations and the sense line reduces frequency response both of which reduce measurement fidelity markedly.

This investigation was performed to research currently available designs which could be utilized for space vehicle applications in cryogenic systems to an accuracy of 2 percent excluding other environmental error sources.

Inquiries made to approximately 50 manufacturers resulted in seven favorable responses from suppliers indicating the availability of transducers operable with cryogenic systems of liquid oxygen or liquid hydrogen. Manufacturers responding favorably to the survey were:

<u>Manufacturer</u>	<u>Transducer Type</u>
Bell & Howell/Consolidated Electrodynamics	Unbonded Strain Gage
Bourns Inc.	Potentiometer
Dynasciences Corporation	Bonded Strain Gage
Genisco Technology Corp.	Bonded Strain Gage
Kistler Instrument Corp.	Piezoelectric
MB Electronics	Bonded Strain Gage
Stalham Instruments Inc.	Deposited Strain Gage

A number of other manufacturers are known to have developed pressure transducers operable in cryogenic systems but these designs are available on special order only and thus were not included in this study primarily due to the lack of descriptive information on the instruments.

This investigation concluded that for the many application conditions of a space vehicle, none of the candidate instruments could meet the design goal of 2 percent temperature sensitivity error. Based on this conclusion, problems contributing to temperature sensitivity were investigated through research of published documents.

The single most important error source for instruments found by the researchers is the difference in temperature conditions between instrument calibration and the using temperature environment. Normally transducers are calibrated under a steady state, uniform temperature environment, usually at the liquid nitrogen temperatures. In field applications temperature gradients occur between the front face of the transducer to the aft end of the instrument. For transducers with temperature compensation provisions such as the strain gage designs, the compensation thermistors and resistors are located in the aft end of the instrument. This design alone contributes to a significant error found by one researcher to be as much as 100 percent FS for transducers that indicated less than 6 percent FS shift in standard steady state temperature tests.

A definite improvement in low temperature performance can be achieved on the part of instrument users by providing installation designs which minimize thermal gradients, such as by insulating the transducer, and by calibrating instruments under conditions of usage as closely as possible.

The conclusion of this investigation is that for applications requiring good temperature compensation, small size, low heat capacity and high frequency response with the capability of measuring both steady state and dynamic responses a new transducer design is required. Based on the information provided by researchers some design features known to provide desirable performance characteristics are: flush diaphragm design with diaphragm machines integral with the case, small case size with short body length and low thermal mass, strain gage design with gages mechanically coupled to the diaphragm in an unbonded configuration, temperature compensation circuitry located in the same thermal environment as the strain gages and transducer installation provisions which facilitate insulation provisions to minimize thermal gradients.

HIGH PRESSURE FLANGE SEALS

This investigation primarily addresses itself to the search for a metallic seal for cryogenic temperature and up to 5000 psig pressure applications.

The leakage rate for a seal depends on fluid properties, surface topography, pressure differential, hardness of the sealing material, and sealing contact stress.



The most important design considerations are pressure, temperature range, and type of fluid sealed. These parameters determine the bolt size, flange thickness, and materials.

Leakage is the most important criterion and most difficult to predict without tests. Many metal seals are capable of achieving leakage rates below measurable levels; however, the penalty in flange loading, extremely smooth finishes or loss of recovery, may be prohibitive. For extremely low leakage rates (less than 10^{-8} scc/sec), an all-metal seal is usually required.

Seating load is an important parameter in flanged connections. The lower it is, the smaller the required flanges and bolting. Seating load is normally expressed in pounds per inch (lb/in) of seal circumference and may range from 100 to 500 lb/in, depending on the design.

Contact stress at the sealing interface partially determines leakage rate and is a function of seating load and contact area. The pressure differential across the interface, if high enough, may add or subtract significantly from the initial contact stress.

Metal seals capable of very low leakage rates must plastically deform at the sealing interface. With subsequent installations, the seal coating must try to conform to a new set of peaks and valleys and intimacy of interface is consequently reduced.

Pressure compensation, sometimes called pressure energization, pressure actuation, or pressure assistance, is the beneficial effect of pressure upon the seal contact. The geometry of many seals is such that fluid pressure augments the contact stress, thus tending to overcome the increased possibility of leakage due to the pressure. The pressure effect is negligible except at high pressures - 1000 psi or more.

Cavity requirements of the seal must provide for correct (limited) deflection of the seal, location of the seal, structural support for high pressure, and proper surface finish.

The choice of seal materials is usually determined by the operating temperature, although corrosion resistance, fluid compatibility, and radiation effects may also be major considerations. Most metal seals contain two materials, a resilient, basic-shape metal and a soft coating.

The coating material is usually a pure metal (silver, gold, nickel, or copper) or a plastic dispersion coating such as Teflon. Coating materials are chosen on the basis of softness, corrosion resistance, temperature resistance, and cost. Silver is used in the majority of low and high temperature applications and is one of the least costly.

Resilient metal seals combine the efficiency of elastomeric O-rings with the extended temperature capability of metal gaskets. The basic structural element is usually a high-strength metal, and a soft coating of metal or plastic provides the actual sealing. Like O-rings, these seals are self-energizing, have small cross sections, require light closing forces, are often reusable, and

have indefinite life. Unlike O-rings, however, they are relatively expensive, and availability is somewhat limited.

Resilient metal seals can be considered as the most promising for achieving seal integrity for high pressure and cryogenic environments. A parallel loaded joint with a groove type seal installation should provide the optimum joint configuration.

HYDROGEN EMBRITTLEMENT OF TRANSDUCER MATERIALS

The research work performed within the industry on hydrogen embrittlement of metals has not resulted in a clear definition of accepted standards. Because of this fact, no precise conclusions can be reached on the extent of hydrogen embrittlement as a problem for instrumentation systems. Primarily, this uncertainty results from the fact that most testing has been accomplished at 10,000 psi and pressures for liquid or gaseous hydrogen systems on Saturn S-II type vehicles are 100 psi to 1000 psi.

Generally, it is concluded that no problems exist for materials most often used for transducer construction. This conclusion is based on the experimental findings that embrittlement susceptibility increases with increasing temperature above room temperature and increasing pressure. Below room temperature embrittlement susceptibility decreases with decreasing temperature. Hydrogen has little effect on metals below a temperature of -321 F. From the standpoint of instrumentation systems, this is favorable since the majority of measurements in hydrogen systems are made at low temperature and pressures.

The report summarizes the degree of susceptibility for various metals where data are available.

THE EFFECT OF CLOSE COUPLED VS. REMOTE TRANSDUCER INSTALLATIONS ON PRESSURE MEASUREMENTS

The measurement of frequency over a line length of constant diameter to which is attached a sensing transducer varies as the fundamental (fd) frequency. If the media transmitting the frequency is a gas, then the frequency is limited by the line length and the acoustic velocity. The exception to this is a situation in which the volume of the transducer cavity measuring the pressure pulse is large relative to the volume of the line. This case is called a Helmholtz resonator and it will produce an attenuation of approximately 40% over the previously noted fundamental frequency for the equivalent line length.

If frequency of pulsations of a liquid over a line is required and if the liquid is a cryogenic, a multitude of problems arise. Pressure pulses of large amplitude will produce complete distortion of phase, frequency, amplitude and signature. Small pressure pulsations will allow the passage of phase and amplitude data within the fundamental frequency range but amplitude and signature cannot be considered correct. The turbulence produced by the



pressure pulsations forces the liquid down a gas filled line where it expands due to the sudden temperature gradient. The resultant change in momentum of the mass of cryogenic liquid in motion and the volume change produces an overall distortion of the output.

The accurate measurement of fidelity of a cryogenic liquid can only be obtained by using either a close coupled or flush mounted transducer. The ideal installation is that of mounting a pressure transducer diaphragm directly against the media to be measured. If this is not possible then the sensor can be boss mounted off a fitting. Care must be taken in the last instance in that a short run from the liquid to the sensor diaphragm might form a Helmholtz resonator.

TECHNIQUES IN TEMPERATURE COMPENSATION OF STRAIN GAGE PRESSURE

The classic techniques for compensation of pressure transducers to temperature sensitivity is to select materials with desirable performance characteristics and to apply compensating resistors and thermistors to the bridge circuitry. These techniques compensate for zero shift and sensitivity changes.

Manufacturers can further improve transducer performance by locating the resistors and thermistors in the same thermal environment as the temperature sensitive member. Instrument users can insulate instruments to stabilize temperature and can apply corrections to calibration curves for zero shifts determined from a reference pressure test.

CRYOGENIC MASS FLOW MEASUREMENT TECHNOLOGY

The object of the cryogenic flow study was to establish the state-of-the-art and to recommend either a specific flow system or if that was not possible, to establish a direction for future development.

The measurement of cryogenic mass gas flow depends upon the determination of several variables. If the measurement is made either inferentially or directly, a compensation of variables must be taken into consideration. Density is always common to an inferentially mass measurement with either a velocity or velocity squared measurement required. Since density itself can be a function of pressure, temperature, torque or damping ratio an inferential measurement of flow can consist of a great deal of variables; some of which can cover a large range. In the direct measurement of mass flow the output can be a measurement of linear or angular momentum or heat transfer. Although the output can be a single variable the mechanism required to generate the output can be extremely complex and limited in range. In addition to the above noted problems, there are a number of material, installation and design problems that also must be solved.

The initial 62 manufacturers reviewed were reduced to 16 candidate systems. These candidate systems consisted of six true mass flow meters and eleven inferential mass meter systems. In addition to manufacturers of flowmeters, such associated problems as facility calibration and previous



data were reviewed. After analyzing all candidate systems, previously run test data, test facilities and the National Bureau of Standards at Boulder, it was concluded that no flowmeter had a proven history of meeting the requirements. Two system types looked promising -- the turbine-capacitance densitometer inferential meter and the heat transfer mass momentum meter. Of these two systems, only the inferential turbine candidate had some data at a cryogenic gas temperature and hence is the recommended choice.

CRYOGENIC LIQUID DETECTION TECHNOLOGY

This section covered twelve propellant gaging systems offered by nine manufacturers. Five of the systems are applicable to positive g applications and seven are applicable to both positive and zero g usage. These systems can be further categorized into five basic operating principles. These are point sensor, capacitance probe, radio frequency, infrasonic, and nucleonic systems. Point sensors and capacitance probes are only useful in positive g environments. The infrasonic and nucleonic systems are applicable in zero g environments, however, both designs are still in the development stage and at this time impose a high weight penalty to obtain good accuracy.

The use of the more standard coaxial cylinder capacitance sensor system for continuous gaging of propellants is not practical due to the capillary rise that occurs at low gravity conditions. The capillary rise for LH₂ and LOX is on the order of 40 and 20 inches respectively for capacitance sensors similar to those used in the Saturn S-II stage.

Since future space vehicles operate under both zero g and positive g environments, no single concept of propellant gaging provides the desired accuracy under both conditions. The results of the study indicate that the radio frequency system is best for propellant monitoring during zero gravity periods when propellant tanks are less than half full. During periods of positive g the discrete level sensing system offers the best accuracy especially during propellant loading and for monitoring the liquid level with tanks full. The best design compromise appears to be a system utilizing both the RF system and discrete level sensors for all phases of the vehicle operation.

CRYOGENIC TEMPERATURE MEASUREMENT TECHNOLOGY

Commercial cryogenic thermometers are available which are capable, under carefully controlled conditions, of precisions greater than ± 0.05 K. However, such precision can only be obtained under static or quiescent conditions. When thermometers are required to respond to rapid temperature fluctuations such as occur in the cooldown of propellant lines, the indicated temperature may depart significantly from the "true" temperature. The loss in validity of the measurement does not reflect a degradation in accuracy of the temperature sensor, but rather indicates that the temperature of the sensor is not at all times the same as the surroundings.

The terms "accuracy" and "reproducibility" require some explanation pertaining to temperature transducers. Accuracy is the significance with which the thermometer can indicate the absolute thermodynamic temperature. This includes errors of calibration as well as errors due to nonreproducibility. Reproducibility is the variability observed in repeating a given measurement using



different thermometers of the same type. Changes produced by thermal cycling of the thermometer to and from ambient are also included in this parameter.

Temperature sensor materials can be divided into three categories: pure metals, non-metals, and thermoelectric devices called thermocouples. While there exist a number of pure metals that are more or less suitable for resistance thermometry, platinum, primarily because of many favorable characteristics, has become predominant as a temperature measuring element. Desirable features such as ready availability in high purity and extensive knowledge about platinum's behavior down to 20 K have tended to perpetuate its use. Its principal disadvantages are low resistivity and insensitivity below about 10 K.

Copper, nickel and tungsten have also been exploited as temperature sensing elements. Copper is inexpensive and has a very linear temperature/resistance relationship. Copper has poorer stability and reproducibility than platinum and its low resistivity is undesirable when a high resistance element is required for temperature measurements below 100 K. Nickel is widely used over the temperature range of 170 K to 575 K; however, this report was primarily concerned with temperatures below 100 K and at this temperature, very little work has been done with nickel. Tungsten sensors are less stable than other metal sensors because full annealing is impractical. At low temperatures the percentage change in resistance per degree is much less than platinum. Tungsten's great mechanical strength allows extremely fine wires resulting in convenience for manufacturing sensors having high resistance values, but this is not important unless the probe resistance must be larger than 5 or 6 thousand ohms.

Non-metals such as semiconductors, carbon resistors, and thermistors are used as temperature sensing devices in the laboratory with some advantages over pure metals. The greater disadvantages for their usage on a space vehicle within the temperature range of 20 to 100 K tend to discount them as a serious consideration unless further development and knowledge is pursued.

Germanium semiconductors are available from several commercial sources. The sensing element is a small single crystal with high resistivity. The resistance/temperature relationship is very complex and requires many calibration points when used over a wide temperature range. The reproducibility is poor and thermal cycling causes drift to occur. This affects their interchangeability drastically.

Carbon resistors have been used as temperature sensors at extremely low temperatures. Carbon has a high sensitivity in the temperature range of 0.1 K to about 20 K; however, above 20 K the dR/dT is very unstable.

Thermistors are inexpensive and very sensitive to temperature. They are small in size and have a high resistivity. Thermistors have a nonlinear R-T relationship and poor stability. Because of the nonlinearity, numerous calibration points are required. A single thermistor is generally unsuited for wide temperature spans because its resistance goes from values which are so high to be inconvenient to values which are too low to be measured with conventional signal conditioning equipment. Several thermistors must be used to cover a wide temperature span.



Thermocouples in comparison with other temperature sensors have certain advantages. The temperature sensitivity span can be small, and is more flexible for installation. The thermocouple is a device of comparatively low cost, high accuracy, wide measurement range, fast thermal response, ruggedness, and reliability. Some of the more obvious disadvantages are the very low output voltage requiring more complex and costly signal conditioning equipment, and the homogeneity of the materials used to manufacture thermocouples is such that interchangeability without complete recalibration is impractical.

After an objective analysis of the different methods of temperature measurement in the 20 to 100 K range, the wire wound metal, especially platinum, is best suited for measurements where high accuracy and stability is required. The thermistor is best for point measurements and the thermocouple best for high temperatures or for rough indication of temperatures.

Resistance bridges are used as a comparison device for measuring precise resistance ratio relative to temperature change of a platinum thermometer. In making comparison resistance measurements for attainment of a high degree of precision, of the order of 1.0 PPM, the following design considerations should be evaluated when selecting a particular bridge design: effects of lead resistance, thermoelectric emf's, self-heating, reactance, bridge linearity, noise, interaction, bridge sensitivity, and accuracy.

From the numerous available bridge designs, a designer has to determine as to which of the bridge designs is most suitable for use for a particular design application. Therefore, in order to establish a methodical design approach, these numerous bridges are described in its basic form as either a full or half bridge. These basic bridges are then evaluated for its advantages and disadvantages based on applicable design considerations. In the process of evaluation, these basic bridges are reconfigured for use as either symmetric or asymmetric configuration and as a low level or high level bridge output based on the importance of a particular design consideration. A table depicting the advantages and disadvantages relative to the various design considerations has been prepared to provide direction in the design approach.

Lead resistance is widely accepted as a major problem in a temperature measurement system design. Because of this problem, numerous bridges such as Mueller, Smith, Siemens and numerous others have been developed since 1871. Each bridge has merits in leadwire resistance compensation, and therefore each is discussed in this report. Variations used in these bridges can then be adapted to the basic bridge selected for the best lead resistance compensation.

HIGH TEMPERATURE STRAIN GAGE TECHNOLOGY

The objective of this section of the components technology report was to review current strain sensing devices and evaluate their performance in a 1500 F to 2000 F airborne thermal environment. The evaluation consists of comparing gage principles of operation, gage materials, gage attach methods, installation techniques, performance characteristics and gage availability.



Space Division
North American Rockwell

A literature survey was conducted which resulted in the selection of three strain sensing devices for evaluation:

- a. Electrical resistance strain gage
- b. Electrical capacitance strain gage
- c. Thermal-null strain sensor

The resistance strain gage operates on the principle that when a load is applied on any material, that material will expand or contract causing strain within the material. If a grid of wire is bonded to the material, it will stretch or be strained exactly as the surface of the test material is strained. This stretching and compressing of the grid wire causes a change in the electrical resistance of the wire which is proportional to the strain in the test member.

One of the major contributors to errors in high temperature strain gage applications is the effects of apparent strain. In a resistance gage, apparent strain causes a change in resistance of a mounted gage due to a change in temperature without an applied load on the test specimen. In an effort to reduce this apparent strain error, temperature compensation is included in the gage designs.

Many resistance gage alloys have been tested in an effort to extend the upper temperature limits. Most alloys exhibit a solid solution phase change below 1200 F. This phase change causes an anomaly in the resistance vs. temperature curve and yields an unsatisfactory alloy for high temperature strain gage usage. Platinum-tungsten alloys are currently the best available for high temperature resistance strain gages.

Attachment of high temperature resistance strain gages can be accomplished by using ceramic cement, aluminum oxide flame spray or by welding. The method used depends upon the material of the test specimen.

There are many resistance gages on the market today. However, only a relative few advertise the capability of operating at 1500 F and none at 2000 F.

Since 1968, Hughes Aircraft, and Wright Patterson Air Force Flight Dynamics Laboratory have coordinated on the development of a high temperature capacitance strain gage. This gage operates on the principle that variations in the gage dimensions caused by strain in the test specimen will change the capacitance of the gage. This change in capacitance is then directly proportional to the strain in the test specimen. The configuration selected for the capacitance gage was a parallel plate gage mounted in a rhombic frame. The gage consisted of a capacitance wafer containing stainless steel plates with mica dielectric insulator, mounted in a stainless steel rhombic stress frame.

3.0 CRYOGENIC PRESSURE MEASUREMENT TECHNOLOGY

Pressure measurements associated with cryogenic systems have most frequently been made by locating the transducer away from the severe low temperature environment. In more recent applications, the practice has changed so that transducers are installed directly in the sense port for greater measurement fidelity. This trend has been brought about by the changing requirements for more precise analysis of system performances especially under transient pressure conditions such as for rocket engine performance during engine startup and shutdown and during oscillating conditions resulting from combustion instability or vibratory interactions. In other vehicle system areas, greater improvement in measurement accuracy is required for measuring launch critical pressures for reducing uncertainties in the launch decision.

This trend toward directly installing the transducer into pressure sense ports of the cryogenic system has created a temperature sensitivity problem for transducer manufacturers and users alike. In an attempt to keep measurement system error within generally acceptable limits of five percent of full scale or less, instrumentation engineers are constantly in search for a transducer capable of satisfactory operation in the cryogenic environment. This study is an attempt to satisfy this need with an investigation into currently available pressure transducer designs.

3.1 TRANSDUCER REQUIREMENTS

The objective of this investigation is to locate a pressure transducer capable of use with liquid oxygen or liquid hydrogen systems. The principle goal of this investigation is to locate a transducer that is capable of operating under the low temperature and fluid conditions of cryogenic systems with a temperature sensitivity error no greater than two percent full scale. The transducer shall also possess performance and environmental characteristics specified in later sections of the report; however, the principle requirement shall be with respect to temperature sensitivity. In previous applications, temperature sensitivity errors and measurement errors due to the volatility of the cryogen have been the prime reasons for large errors in making these measurements. The value of two percent full scale has been selected to maintain a measurement system error within the commonly accepted limit of five percent full scale.

3.2 MEASUREMENT DESCRIPTIONS

Cryogenic liquid pressure measurements present an especially difficult problem due to the extremely volatile nature of the measurand. Unless transducers are carefully instrumented to avoid a biphasic condition, the accurate measurement of pressure under an oscillating or fluctuating state becomes difficult due to the change in state from liquid to gas. The oscillation of the measurand causes a flow of liquid into sense lines or transducer cavities which can be warmer than the boiling point of the cryogen. An exchange of heat energy takes place causing the cryogen to convert to gas which expands and tends to drive the liquid from cavities and lines. The effect of this change of state of liquid to gas is to mask the true pressure fluctuations occurring

in the measurand. This condition then is a special problem for dynamic pressure measurements with connecting tubing, voids or chambers.

In addition, the measurement of cryogenic pressure presents a number of transducer performance and application problems related to the temperature environment. Liquid hydrogen and liquid oxygen propellant systems present wide extremes of temperature environments, especially under conditions where the cryogen in a feedline changes from a state of non-flow to flow. Rapid energy exchange takes place under the flow condition and temperature gradient problems across the transducer are extremely severe during the initial period of flow. Some of these measurement conditions are discussed in the following.

Typical pressure measurements associated with a large-scale space vehicle

Tank Measurements

LOX and LH₂ Pressures
Ullage Gas Pressures

Feedline Measurements

LOX and LH₂ Pump Inlet Pressures
LOX and LH₂ Pump Discharge Pressures
Feedline Pressures
Valve and Regulator Pressures

Engine Measurements

Thrust Chamber Pressures
LOX and LH₂ Injection Pressures
Regulator Outlet Pressures

Pressure measurements associated with LOX and LH₂ systems can be instrumented in three possible configurations. These are depicted in Figure 3.2-1. The three potential configurations are:

Immersion of the measurement transducer directly in the cryogenic liquid.

Direct installation of the transducer into a pressure port or boss which is called a close-coupled installation.

Connection of a transducer to the measurement source through a connecting sense line which is called a remote installation.

Since cryogenic pressure measurements encompass such a wide range of conditions, each application has its own unique requirements for best measurement performance with respect to transducer design and application provisions. This investigation will explore some of these many possibilities.

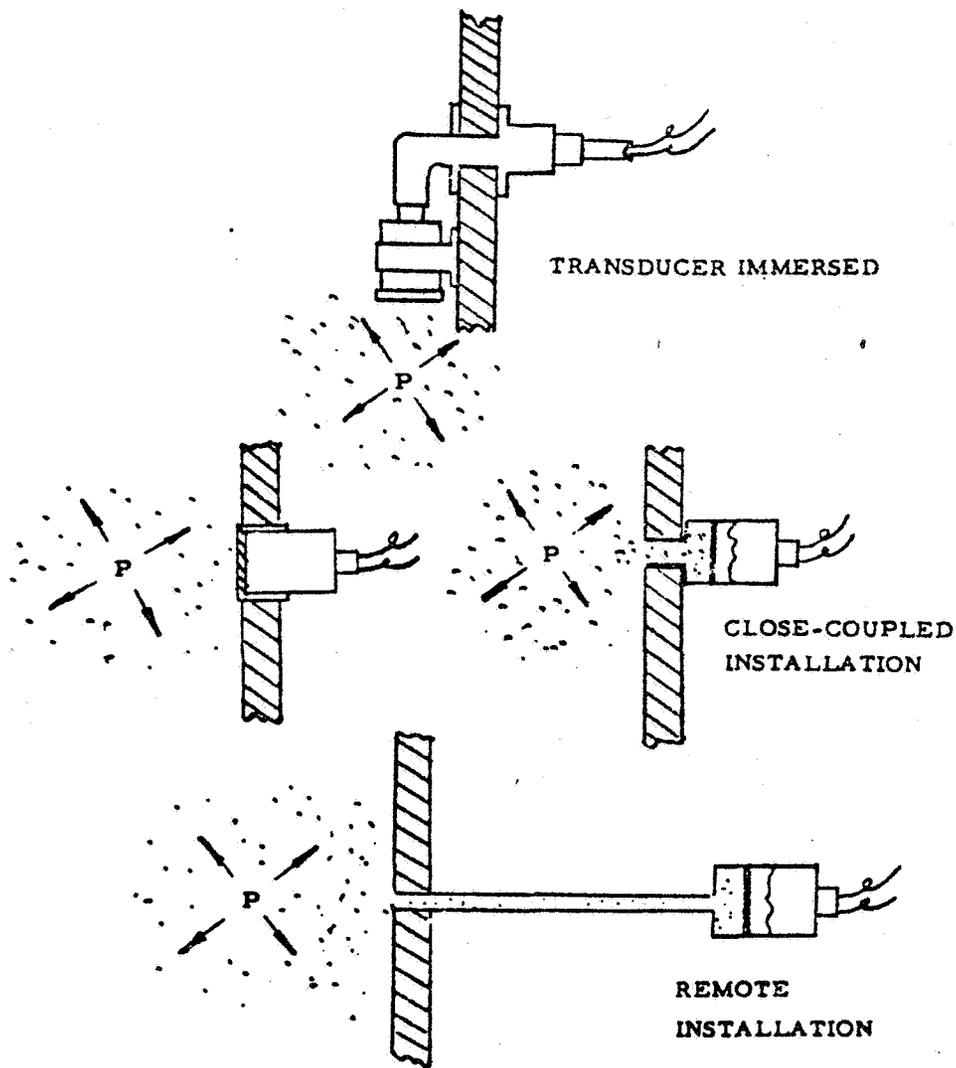


Figure 3.2-1 Potential Transducer Installation Configurations

The pressure transducer associated with these measurements is exposed to a wide variation of temperature environments. For long-term space operations, environmental temperatures may range between -250 to greater than +250 F. During various vehicle and subsystem operations such as tanking, prechilling, propellant flow, engine start and valve and regulator operations, more severe environmental extremes occur. Generally, the worst case transients are those which occur from some ambient temperature to a cryogenic range. Typical data samples from Saturn S-II flight tests [1], [2] are presented in Figures 3.2-2 through 3.2-8.

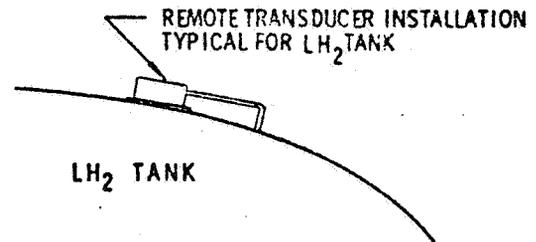
Figure 3.2-2 shows two gaseous pressure measurements using a remotely installed transducer. Both instruments are installed in the proximity of the tanks, thus are subject to a low temperature environment. Transducers used in the Saturn S-II stage application are provided with heaters which are powered up to the time of vehicle liftoff. Measurements utilizing this design are highly accurate; however, the ullage pressure measurements are one of the few cases where a heater can be utilized, since the transducer never measures the liquid pressure. For longer duration missions, transducers capable of operating without the use of heaters would provide a considerable advantage by reducing electrical power consumption and improving measurement quality.

Figure 3.2-3 depicts the pressure measurement of a large tank containing liquid oxygen. The transducer is exposed to the liquid oxygen at the face of the transducer and ambient temperature around the body of the transducer. In the case of the Saturn S-II stage, this measurement was implemented to measure a low frequency oscillation of the LOX system resulting from center engine and vehicle structure vibratory interaction. Moderate measurement accuracy has been maintained by completely insulating the transducer.

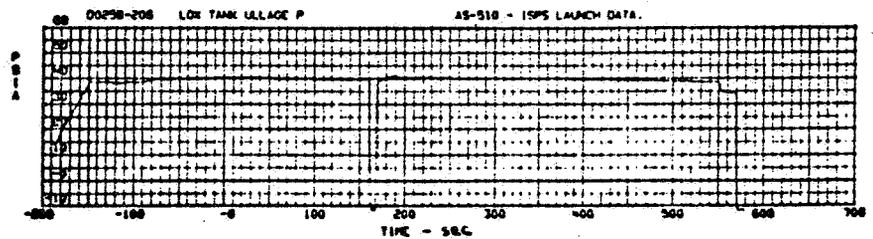
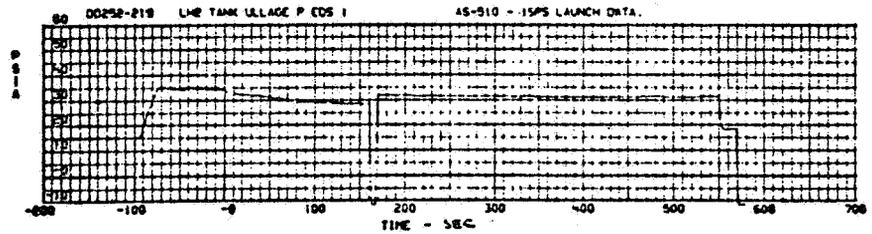
Figure 3.2-4 shows the data from three Saturn S-II engine pump inlet measurements. The D091 pressure measurement is made with a remotely installed transducer and temperature controlled with a heater up to the time of vehicle liftoff. Measurement D267-205 is an internal feedline temperature measurement. D267-205 is intended to measure the same low frequency pressure oscillation as D266-206, the LOX sump measurement. A significant point to be established from the comparison is that a discrepancy in magnitude exists between the two pressure measurements. This deviation is largely attributed to temperature sensitivity of the close-coupled strain gage pressure transducer. A less temperature sensitive transducer would provide more useful data. In addition, a single transducer capable of measuring both the dynamic and steady-state conditions accurately, would provide a significant cost savings.

Figure 3.2-5 shows a pressure and temperature measurement of the engine LH₂ pump inlet. The measurements are similar to the LOX system measurements C663-205 and D091-205 except that no oscillation measurement like D266-206 is made.

Figure 3.2-6 shows the accumulator pressure measurement with a change in pressure taking place during pressurization of the accumulator. Temperature measurement C879-205 is provided to show an approximate temperature profile during

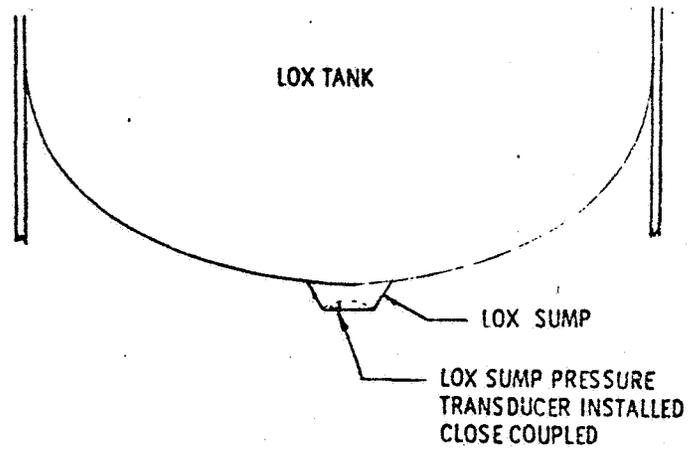


MEASURAND: GASEOUS OXYGEN AND HYDROGEN
 PRESSURE PROFILE: STEADY OR SLOW CHANGING
 TEMPERATURE PROFILE: AMBIENT ENVIRONMENT OF FORWARD SKIRT

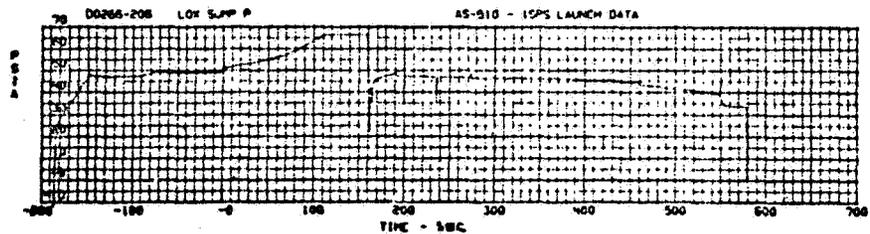


[2]

Figure 3.2-2 LOX and LH₂ Ullage Pressure Measurements

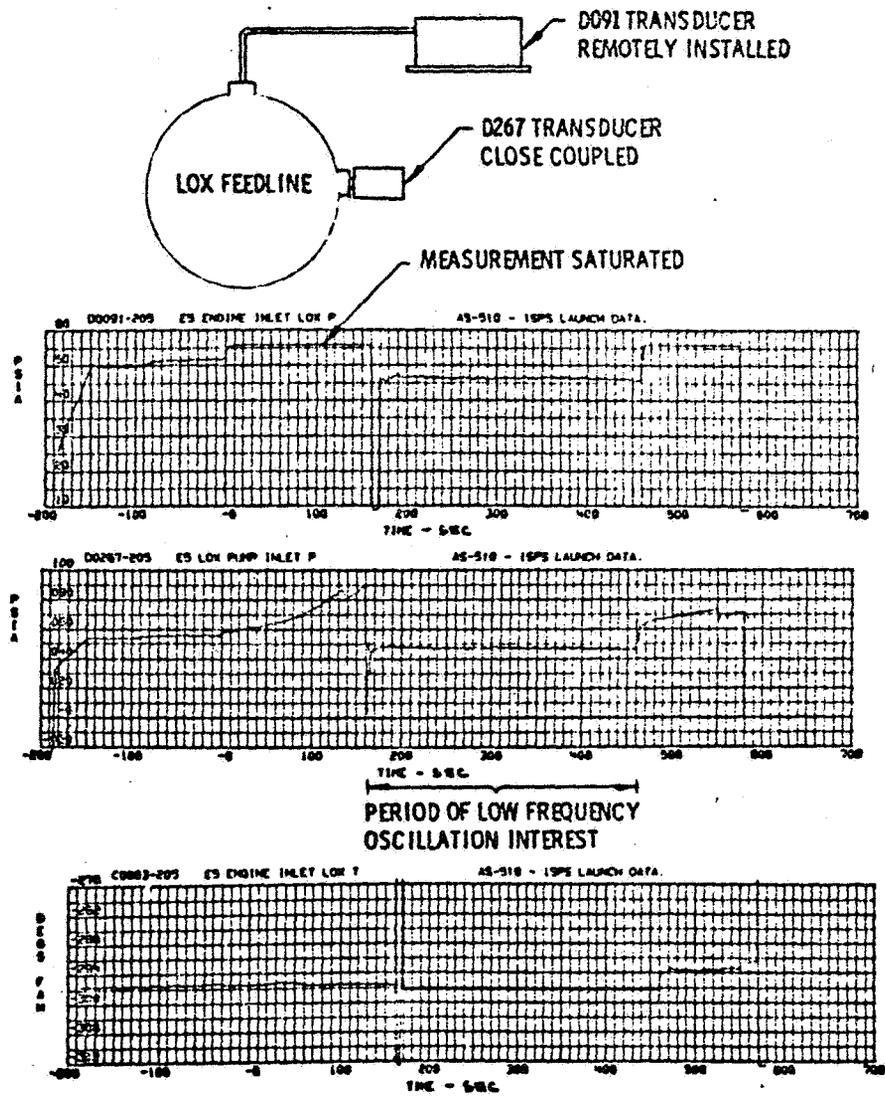


PRESSURE PROFILE: RELATIVELY STEADY OR SLOW CHANGING
TEMPERATURE PROFILE: STEADY WITH A GRADIENT

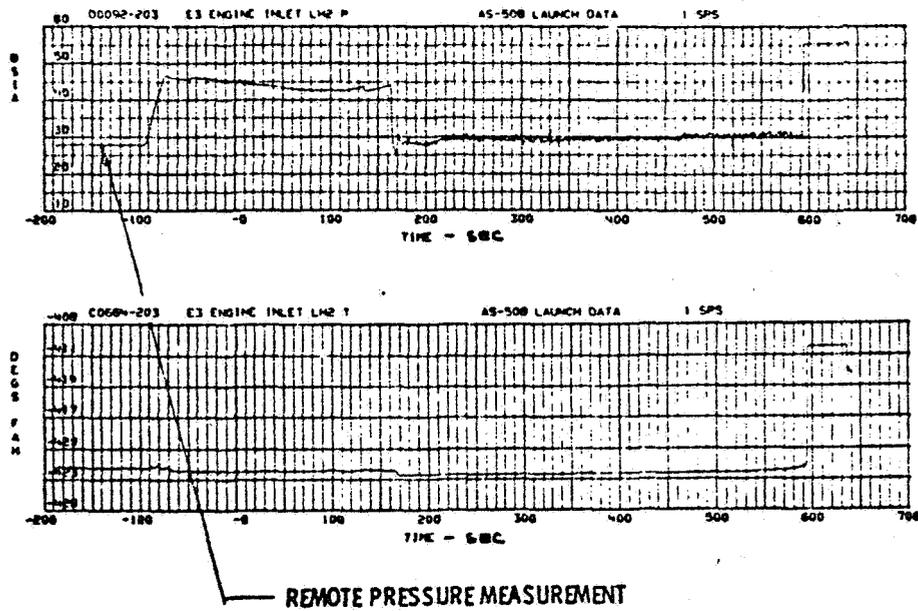


LOW FREQUENCY OSCILLATION
PRESSURE MEASUREMENTS
ARE REQUIRED

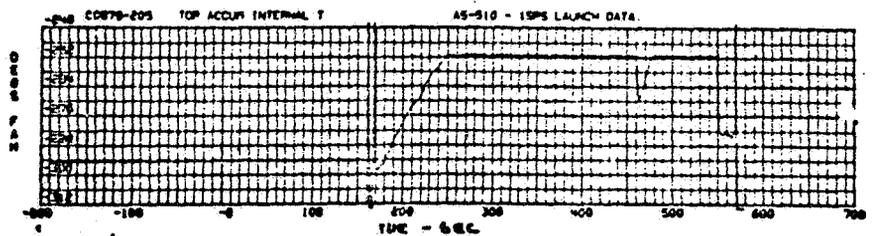
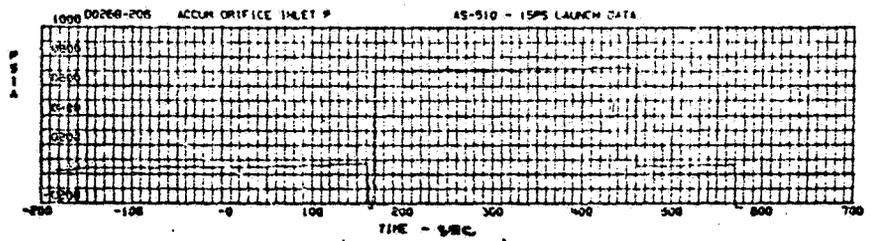
[2]
Figure 3.2-3 LOX Sump Pressure Measurement



[2]
Figure 3.2-4 Engine LOX Pump Inlet Pressure and Temperature

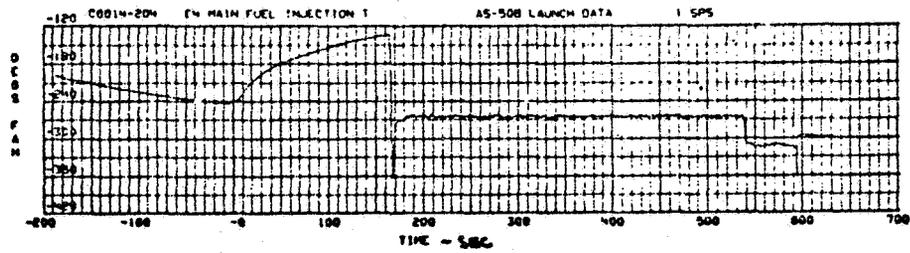
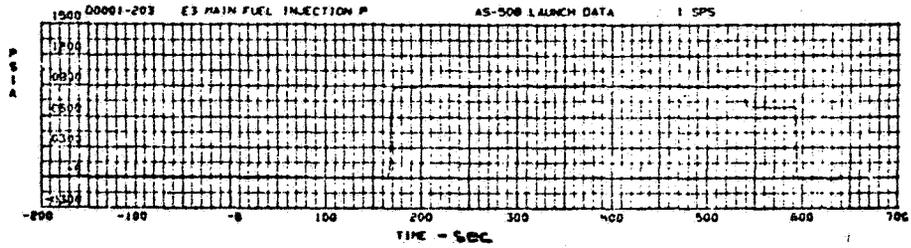


[1]
 Figure 3.2-5 Engine Inlet LH₂ Pump Inlet Pressure and Temperature

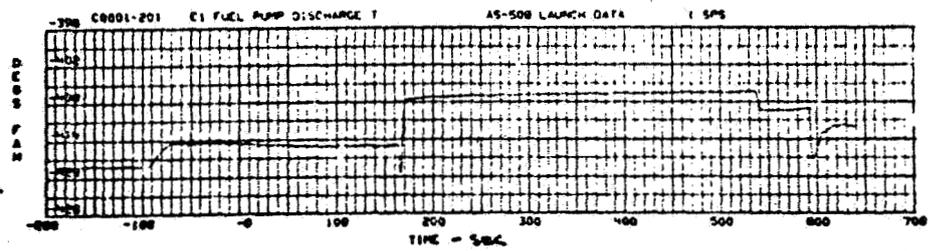
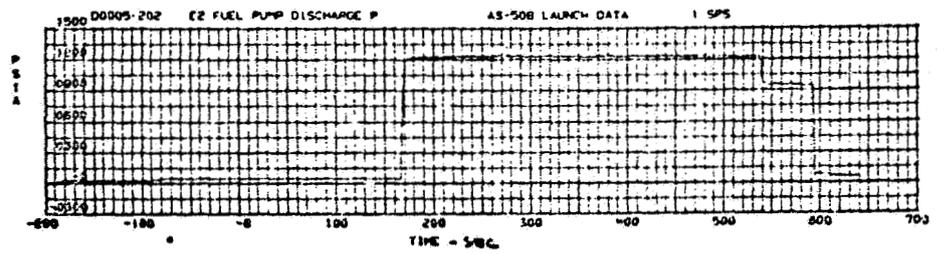


[2]

Figure 3.2-6 Accumulator Orifice Pressure and Accumulator Temperature



[1]
Figure 3.2-7 Fuel Injection Pressure and Temperature Measurements



[1]
Figure 3.2-8 Fuel Pump Discharge Pressure and Temperature Measurements

the pressurization step with this temperature measurement being made in the accumulator rather than at the location of the pressure measurement. This is a case of a relatively mild transient temperature change.

Figures 3.2-7 and 3.2-8 both show pressure steps and temperature profiles of the associated temperature measurements. In the Saturn S-II applications, the pressure measurements are made with remotely installed pressure transducers. Thus, they are relatively unaffected by temperature transients insensitive to high response pressure fluctuations. A close-coupled installation could provide more meaningful data.

3.3 PRESSURE MEASUREMENT DESIGN CONSIDERATIONS, [3], [4].

Pressure transducers for advanced space vehicle applications during prelaunch, launch, and on-orbit operations require transducers which meet a wide range of performance and environmental conditions. Some of these are:

- a. Wide range of temperature extremes
- b. High vibration and shock environments
- c. Moderate to high measurement accuracy resulting from good stability and repeatability
- d. Highly rupture-proof case designs
- e. Small case size and low weight
- f. Low electrical power requirements
- g. Long life capability
- h. Good corrosion resistance and chemical inertness
- i. Convenient transducer mounting provisions

A relatively limited number of transducer designs are available which are capable of meeting the requirements above as well as one or more of the installation configurations of Figure 3.2-1. Pressure transducers are designed as integral units where the sensor and signal conditioning are contained in a single case or as a split package where the sensor and signal conditioning are two separate modules interconnected by wiring only. Transducers with integral electronics are available for cryogenic applications; however, the limited temperature capability of the electronics necessitates a remote transducer installation and, most likely, a thermal protection provision. Because of the requirement for remote installation only, these transducers are limited to measurements of slower responses.

All transducers involved in this study are designed with a force summing member. The force summing member performs the function of converting the applied pressure to a deflection. Designs frequently used are:

Diaphragms
Aneroid Capsules
Twisted Tubes
Helical Tubes

The most common of these selected for space vehicle instruments is the flat diaphragm which is essentially a circular thin plate clamped around its circumference. All candidate transducers identified from the survey conducted in this investigation utilized flat diaphragms except the potentiometric units.

With applied pressure the diaphragm deflects in accordance with the laws of a thin circular plate under conditions of uniform loading. Diaphragms are usually designed so that the center deflection does not exceed half the thickness of the plate in order to maintain a linear relationship between deflection and applied pressure. Where larger deflections are required, corrugated diaphragms are used which allow approximately two percent of the diameter dimension for deflection. In cases where large deflections are required, aneroid capsules or bellows are used. Aneroid capsules are composed of two identical corrugated diaphragms welded together face-to-face at the periphery. Bellows consist of stacks of capsules joined together to form an air-tight cavity. Capsules and bellows are manufactured from a variety of materials with phosphor bronze, Inconel-x and Ni-Span-C being among the most common. Ferric nickel or stainless steel diaphragms are selected for applications of extreme temperature environments due to the temperature stability of these materials. Bourdon tubes, C-tubes, twisted tubes, spiral tubes all operate on the principle that pressure differential between the exterior and the interior of the tube creates a force tending to wind or unwind the tube. Transducers are designed utilizing the principle that if the open end of the tube is held in place, the closed end tends to move. Pressure changes are sensed by attaching strain gages or the slider arm of a potentiometer to the tube.

Coupled to the force summing member either directly or through linkages is the sensor which may employ any one of a number of transduction principles available in the field of transducer technology. Some of the more common transduction techniques are:

Variable resistance - potentiometer
Variable capacitance
Variable inductance
Piezoelectric

3.3.1 Potentiometric Pressure Transducer

The potentiometric pressure transducer represents one of the simplest design approaches for pressure measurements. The instrument operates from a dc source and provides a high level signal output as a function of the applied pressure. The basic operating principle is that the measured pressure is applied to a force summing member (usually a capsule, bellows, bourdon tube, or other tube configuration) which moves a sliding contact over an electrical resistance element. The output voltage is a function of the position of the slider contact on the electrical resistance element and applied voltage across



the resistance element. Most applications use linear potentiometers; however, logarithmic, exponential or sine functions are also available.

The potentiometric resistance element is usually between 0.3 to 0.8 inches in length. For most force summing members except for the bourdon tube and other tube configurations, the motion of the flexible metal element requires amplification through the use of linkages. The relatively large motions required by these transducers also requires relatively large internal volumes and relatively large internal volume change. These design features limit the use of potentiometric transducers to measurements with relatively slow pressure changes and increase the sensitivity of the transducer to vibration and temperature extremes. In addition, friction effects from movement of the linkages and the slider arm contact with the potentiometer require a relatively high force to overcome the frictional effects. The high force requirements generally restrict this design for use in very low pressure measurements and generally result in larger transducers due to the larger capsule sizes required for the higher forces. Diligent design considerations and care in the selection of materials can often overcome many of these limiting design features. Pivotal bearings such as ball or jewel bearing must be selected for low friction, long life, minimum dimensional error, and good vibration and acceleration capability. Oil damping often is utilized to increase vibration capabilities and heaters are utilized to improve low temperature performance. Where oil damped transducers are exposed to temperature much below approximately -65 F, heaters are required to maintain acceptable performance levels, especially response characteristics.

Wiper design is another critical component for potentiometric transducers since wiper liftoff or wiper resonances are often problems which result in signal output spikes or noise. Often the problem results in a tradeoff between increasing wiper pressure against the potentiometer which increases the frictional problem of the wiper on the resistance element. A common design approach in the solution of this problem is to use a double wiper with contacts on either side of the resistance element. This design eliminates the noise due to discontinuities, since at least one wiper maintains contact with the resistance element.

Potentiometers for transducers are constructed in linear and curved shapes of either rectangular or round cross section. The resistance elements can be constructed for a linear output or other non-linear outputs such as a logarithmic function. Precision performance from the resistance element depends on a number of electrical and mechanical considerations. Some of these are:

- Constant specific wire resistance
- Constant resistance and contact resistance with wear
- Low thermo-electric effects
- Constant resistance at variable temperature
- Constant output voltage with variable wiper loads
- Constant insulation resistance values
- Constant wire diameter and pitch winding with environments and usage
- Constant physical characteristics and relationship of the former and wiper



The resistance element wire must be precision drawn and annealed in a reducing atmosphere to avoid surface oxidation. The thermo-electric characteristics of the wire should be protected from surface corrosion by enameling or oxidation. For small gages, the wire must be strong and ductile for winding on the mandril.

Wire resistance stability with time depends upon annealing and upon the ability of the wire material to withstand corrosion. Common resistance alloys in general use are listed below:

- a. Copper-nickel alloys have the lowest temperature coefficient of resistance and a medium-high resistivity. Mechanical strength is adequate but thermoelectric characteristics with copper is very poor.
- b. Nickel-chromium alloys have high resistivity and fairly low temperature coefficients of resistivity. Their resistance depends on the state of annealing. Mechanical strength is high and ultimate working temperatures are high.
- c. Nickel-chromium iron alloys cost less than nickel-chromium alloys but are ferro-magnetic at room temperatures and have higher temperature coefficients.
- d. Silver-palladium alloys have higher resistance to corrosion and thus lower contact resistance.

3.3.2 Strain Gage Pressure Transducers

The application of the strain gage principle to pressure transducer technology is widespread and highly successful. The technique of applying strain gages to a force summing member is adaptable to a number of possible configurations, thus strain gage pressure transducers are available in low to high ranges and in all sizes.

The most common method used in the industry is either to bond the strain gage directly to a diaphragm or other deflection member, such as a beam (bonded strain gage design) or to mechanically couple the strain gages (unbonded strain gage designs) to the diaphragm. Most strain gage pressure transducers are designed with four active strain gage elements connected in a wheatstone bridge arrangement. The gages are installed on the diaphragm or beam so that two gages are in tension and two in compression when deflection of the diaphragm occurs. Connecting two gages so that the resistance increases and two gages so that the resistance decreases in opposite arms of the bridge results in maximum bridge output.

The full scale output of a metal wire or foil gage is approximately 50 to 60 millivolts for bonded gages, and 60 to 80 millivolts for unbonded gages with a 10-volt excitation voltage applied. With the addition of compensating and trimming resistors, the full-scale outputs are reduced typically to 30 millivolts and 40 millivolts. Most applications require amplification of this low level signal to a high level signal commonly 0 to 5 vdc. The signal conditioning can be provided with the electronics contained within the trans-



ducer housing or in a split package. The option of a split package design provides a significant advantage for the strain gage transducer. On a large scale space vehicle, the split package option utilizing a strain gage transducer with a remotely installed dc amplifier can result in considerable cost savings both in the area of measurement hardware and bracketry required. Without signal conditioning, electronics transducer sizes can be made small enough for port mounted installations undergoing severe environmental conditions. This feature is extremely important for cryogenic applications where dynamic response measurements are required. The port installation is the only means available for an accurate reproduction of the pressure fluctuations in the cryogenic lines.

3.3.3 Piezoelectric and Quartz Pressure Transducers

Piezoelectric and quartz materials generate an electric charge with applied stress. This principle is applied to pressure transducer technology through the use of a flat diaphragm which transmits a force to the crystal material directly or through mechanical linkages as a function of the applied pressure. Materials which exhibit the piezoelectric effect are either synthetically fabricated or found in a natural state. Natural crystals are quartz and rochelle salt. Synthetic crystals are lithium sulfate, ammonium dihydrogen phosphate and polarized ferroelectric ceramics such as barium trianate.

Piezoelectric materials respond to mechanical stress in different modes such as in tension, compression and shear. Metal electrodes are plated onto the selected faces of the piezoelectric material for the desired mode of mechanical loading to pick off the generated charge, the electrodes being the plates of a capacitor. The piezoelectric element is thus a charge generator and capacitor. The technique is not applicable to steady state responses since the finite insulation resistance of the transducer circuit and the shunting effect of the load resistance cause the generated charge to gradually leak away.

The crystal transducers offer a number of highly desirable features which cannot be equaled by any other designs currently available. The transducer size is the smallest of all pressure transducers available. In addition, the instruments are characterized by a high natural frequency capability. Transducers are available which weigh less than one gram, and self-contained electronic units for pressure measurements are available which weigh less than 10 grams (not for cryogenics). Temperature capability of these transducers are also extremely good with designs available for direct installation into feedline bosses of cryogenic systems.

The prime limitations of crystal transducers are their lack of steady state response, their high electrical output impedance and the need for low-noise low-capacitance cables.

3.3.4 Variable-Reluctance Pressure Transducer

Variable reluctance pressure transducers operate on the principle that pressure changes on a diaphragm can be utilized to vary the inductance of a coil. Coil inductance variations can be achieved by changing:

- a. The coil geometry
- b. The reluctance of the magnetic Path
- c. The permeability of the magnetic core material
- d. The coupling of two or more elements of a coil

Of the four techniques above, the changing of reluctance of a magnetic path is the most common technique in use.

The variable-reluctance principle is usually designed with a diaphragm of magnetically-permeable material, supported between two inductance elements. An unbalance of pressure on either side of the diaphragm creates an unbalanced force which displaces the diaphragm and results in a change in reluctance in the magnetic path by increasing the gap in the magnetic flux path of one core and decreases the gap equally in the other core. Available pressure ranges for inductive transducer ranges from 0.0 to 5000 psi.

In this investigation no transducers were identified utilizing the variable-reluctance principle.

3.4 SURVEY RESULTS OF CURRENTLY AVAILABLE DESIGNS

The survey of manufacturers reveals that of the approximately 50 suppliers contacted, seven have submitted data indicating the availability of pressure transducers operable at cryogenic temperature ranges suitable for space vehicle usage. The instruments identified utilize one of three sensor techniques either potentiometric, piezoelectric or strain gage. Manufacturers responding favorably to the survey were:

<u>Manufacturer</u>	<u>Transducer Type</u>
Bell & Howell/Consolidated Electroynamics	Unbonded Strain Gage
Bourns, Inc.	Potentiometric
Dynasciences Corporation	Bonded Strain Gage
Genisco Technology Corporation	Bonded Strain Gage
Kistler Instrument Corporation	Piezoelectric
MB Electronics	Bonded Strain Gage
Statham Instruments, Inc.	Deposited Strain Gage

Originally a much larger number of manufacturers indicated the availability of pressure transducer designs capable of operating under a cryogenic environment. Many of these sources could not be identified in this investigation because sufficient data were not available or because the part was not manufactured as a standard commercial item. A number of other manufacturers have transducer designs which appear suitable for cryogenic applications but are not so advertised since tests have not been conducted at the cryogenic environments or tests and test data are not complete. Thus, the results presented herein should not be interpreted as the total industrial capability for cryogenic pressure transducers. The results presented are intended as a reference source for transducer designs readily available as off-the-shelf equipment.

The transducer designs offered by manufacturers as operable at cryogenic temperature are briefly described below. All transducers identified are split package designs capable of direct installation in a cryogenic feedline or tank pressure port. Except for the single potentiometric unit, all of the designs require separate signal conditioning equipment.

3.4.1 List of Manufacturers

3.4.1.1 Bell & Howell/Consolidated Electrodynamics Electronics and Instruments Group [5]

Bell & Howell advertises a total of seven transducers operable at the cryogenic temperature ranges. All are unbonded strain gage designs either flush diaphragm or cavity type. All transducers employ a design of the strain-gage windings connected in a four-arm bridge. All designs utilize a flat diaphragm as the force summing member. Pressure applied against the diaphragm produces a displacement of the sensing element, changing the resistance of the active arms and causing an electrical output proportional to the pressure. The sensing element is a spring assembly which supports the strain gage wire windings. Displacement of the spring assembly resulting from displacement of the diaphragm causes movement of the posts upon which the strain windings are mounted. This movement causes the strain in wires which changes the resistance of the wire thus providing the electrical output change. Figure 3.4.1.1-1 shows one typical assembly which demonstrates the principle used.

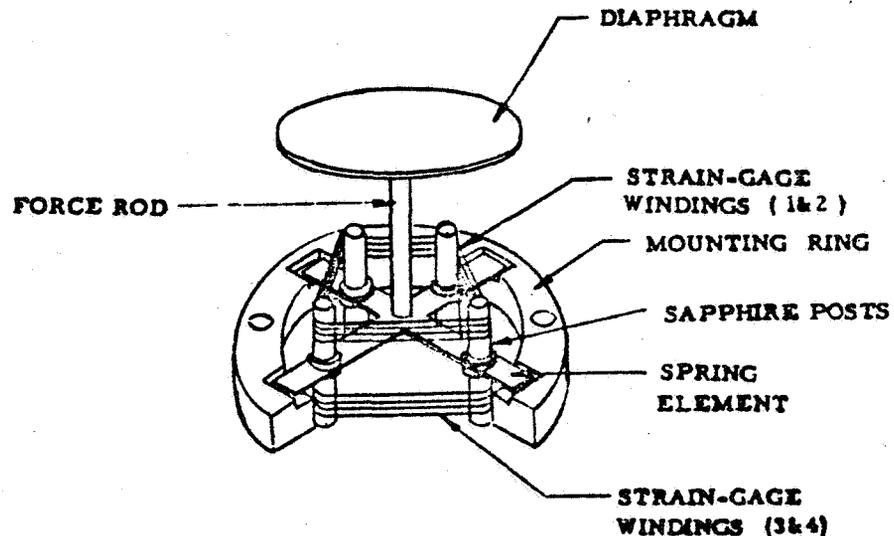
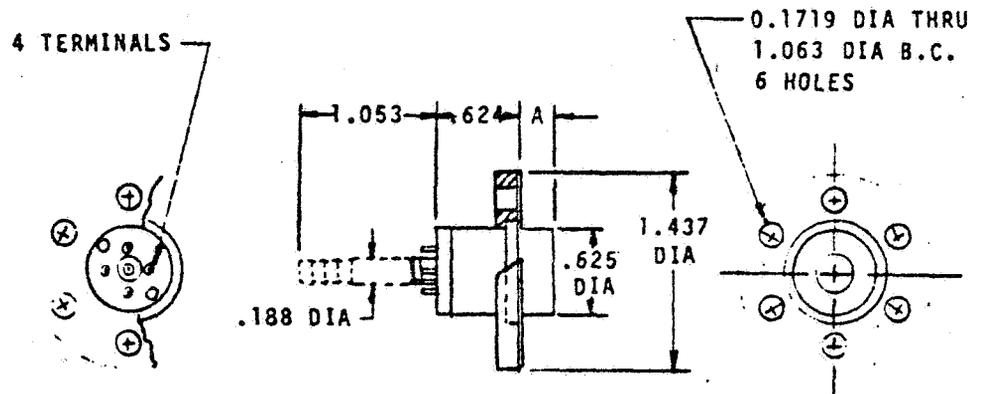


Figure 3.4.1.1-1 [5] Typical Sensor Assembly Design For Unbonded Strain Gage Transducer



A DIM MAX	DESCRIPTION
.231	26 TO 400 PSI
.203	500 TO 3000 PSI
.270	3500 TO 5000 PSI

Figure 3.4.1.1-2 [5] Bell & Howell Type 4-313

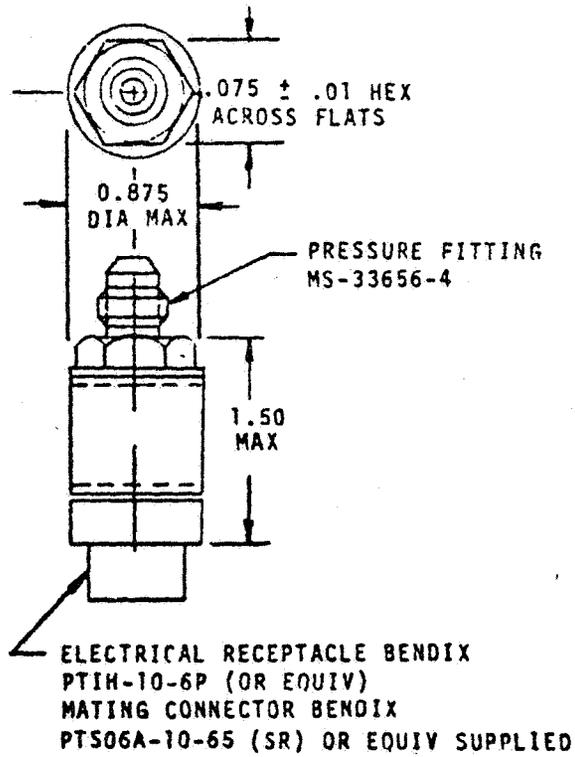
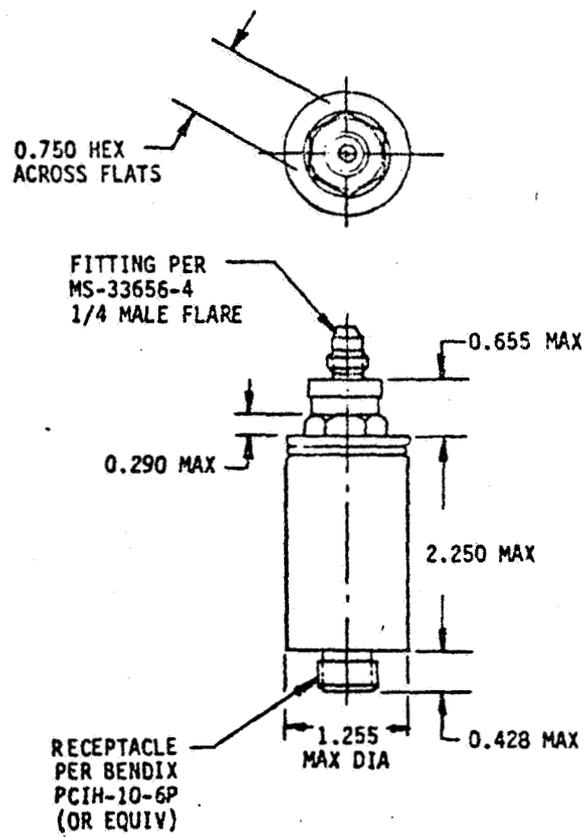


Figure 3.4.1.1-3 [5] Bell & Howell Type 4-356



[5]
Figure 3.4.1.1-4 Bell & Howell
Type 4-361



Space Division
North American Rockwell

Bell & Howell transducer Types 4-312, 4-313, 4-316 and 4-317 are similar in appearance and internal design. The case and diaphragm are constructed in one-piece from 410 stainless steel. Both Types 4-316 and 4-317 are constructed from non-organic materials, special ceramics and feed-throughs, which provide resistance to nuclear radiation effects.

Instrument Types 4-326, 4-356 and 4-361 are cavity units whose case and diaphragm are constructed from 17-4 PH stainless steel. Type 4-326 is advertised as a general purpose transducer offered in a wide range of pressures and performance tolerances. Type 4-356 offers the best temperature performance of the Bell & Howell transducers. Type 4-361 is designed especially for applications involving wide temperature ranges and intense nuclear radiation environments. This unit has the widest advertised temperature capability of all the instruments identified in the survey with a range of -423 to 700 F.

Outline dimensions of transducer Types 4-313, 4-356 and 4-361 are provided in Figures 3.4.1.1-2, -3, and -4 as typical examples of the Bell & Howell product line.

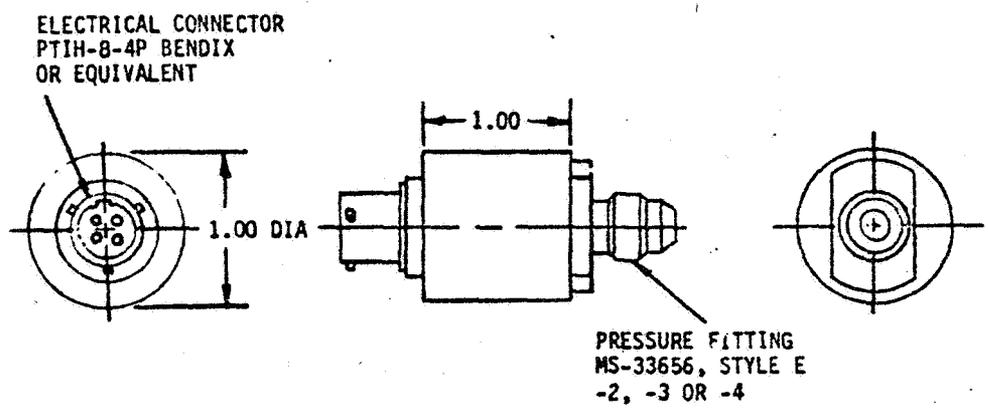
3.4.1.2 Bourns, Inc.

Bourns Models 434, 441 and 534 are potentiometric pressure transducers designed for cryogenic temperature service. Models 434 and 534 cover low pressure ranges to 5 psia and psid ranges, respectively. Model 441 covers high pressure ranges to 500 psia.

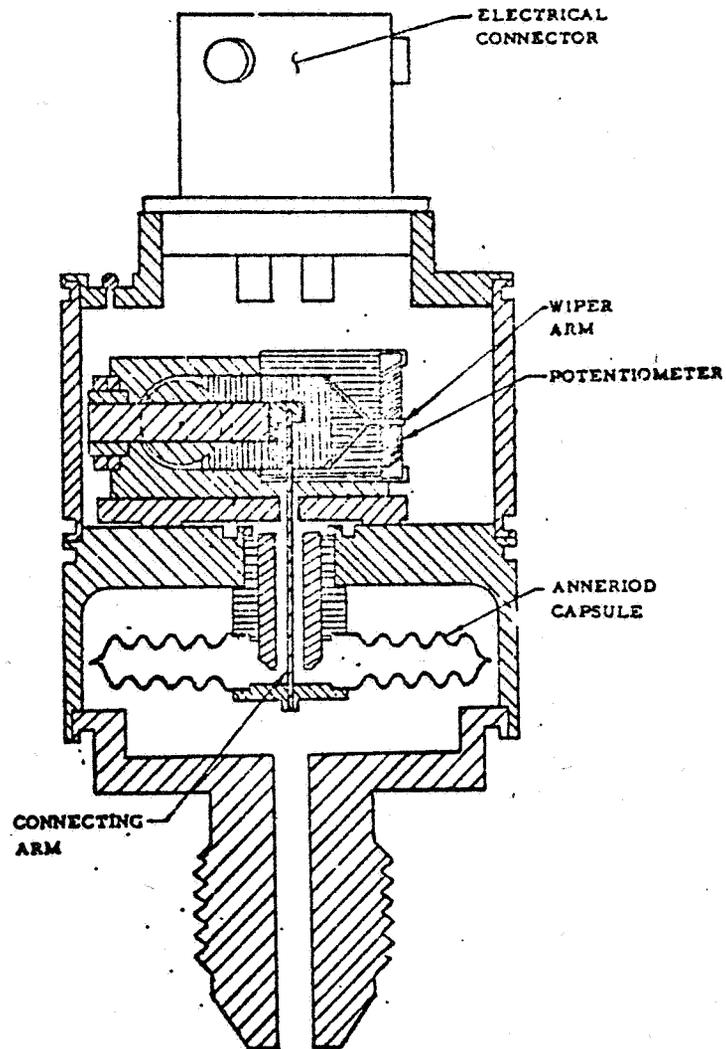
Model 441 is one cubic inch in size with a weight of 2-1/4 ounces. The instrument is designed to provide a linear, high-level voltage output with pressure variations. The transducer is operable with excitation voltage compatible with a power rating of 1 watt at 165 F.

The Model 441 utilizes an aneroid capsule for a force summing member with the free end of the capsule attached to a strut wire which, in turn, is fixed to the potentiometer wiper arm assembly. The arm is free to rotate about a pair of crossed strip flexure pivots. Contact of the wiper arm to the potentiometer is made with a small diameter wire constructed for light weight and strength. Pressure applied to the pressure port fitting deflects the free end of the aneroid diaphragm which transmits this linear motion to the wiper arm through the strut wire. The strut wire is attached to the short portion of a motion multiplying lever whose free end carries the element wiper contact. The mechanical lever multiplies the strut wire motion by approximately four times in rotational motion of the wiper across the output potentiometer. The two crossed strip flexure pivots provide frictionless bearings and support for the motion multiplying lever. Adjustable counter weights on the short end of the lever provide counterbalance correction from acceleration and vibration.

The transducer is packaged so that the force summing member, the potentiometer and all linkages are mounted on the most rigid center section of the all-welded case. A positive mechanical stop design is provided so that the deflection of the free end of the capsule is controlled in the direction of the applied pressure. Temperature performance capability is achieved by mechanical

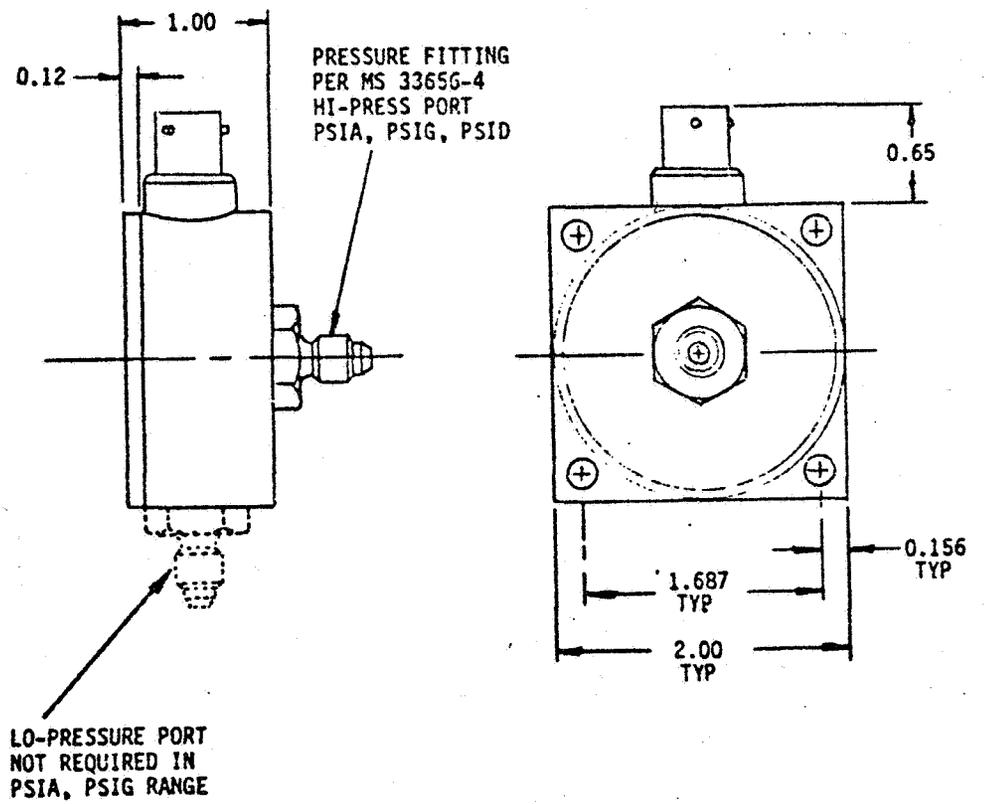


[6]
Figure 3.4.1.2-1 Bourns Model 441



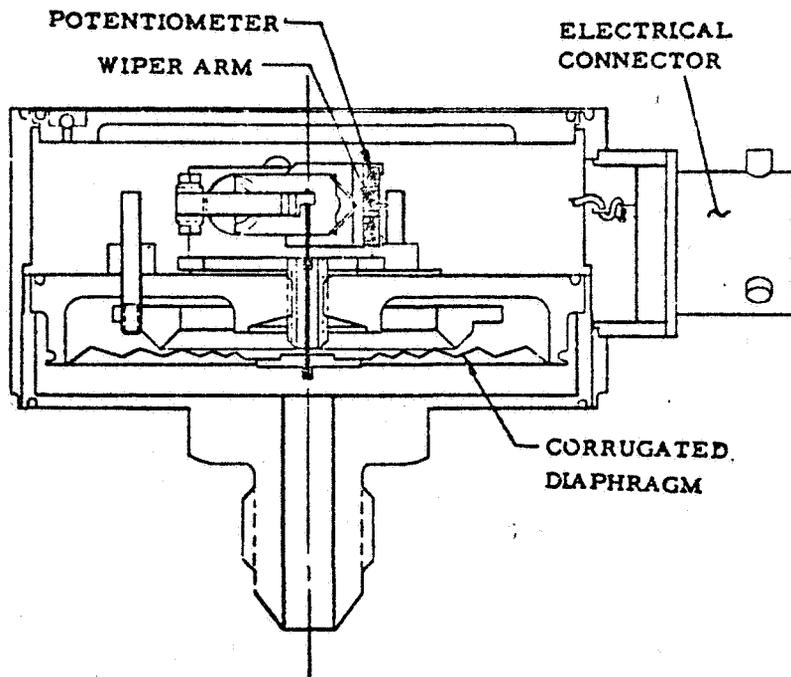
[6]

Figure 3.4.1.2-2 Bourns Model 441 Internal Design



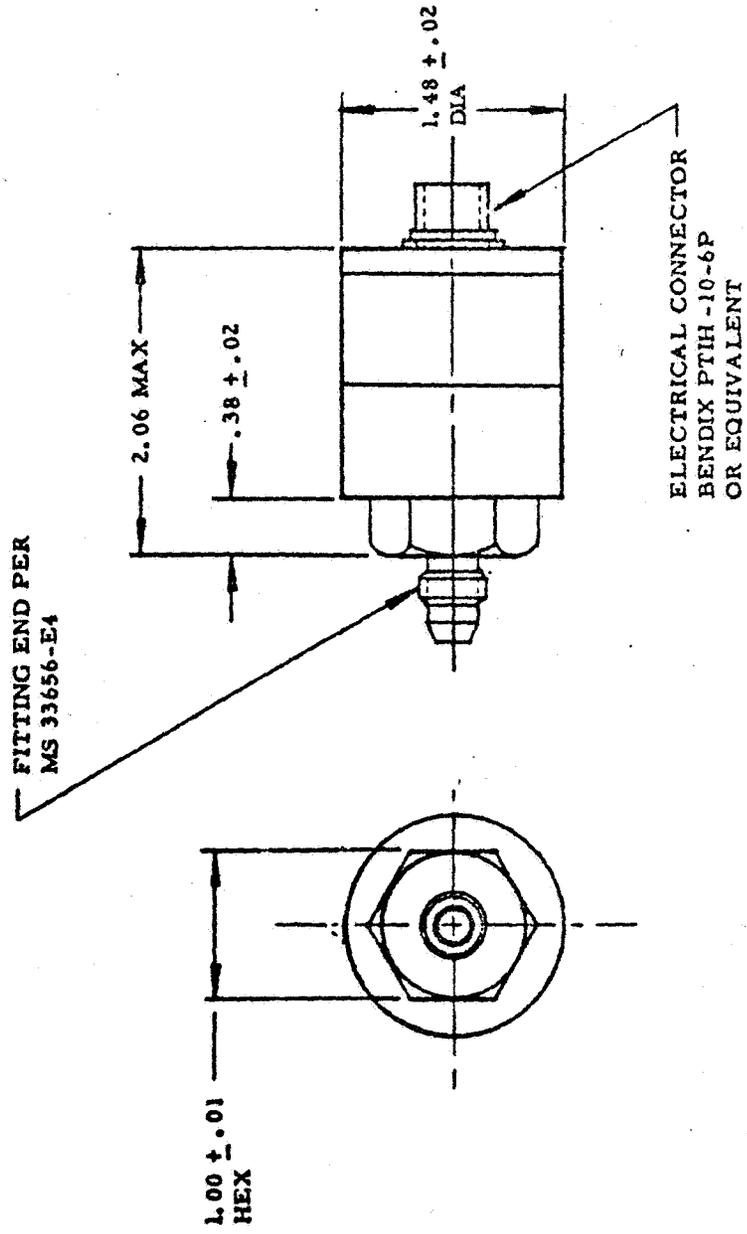
[6]

Figure 3.4.1.2-3 Bourns Model 434/534

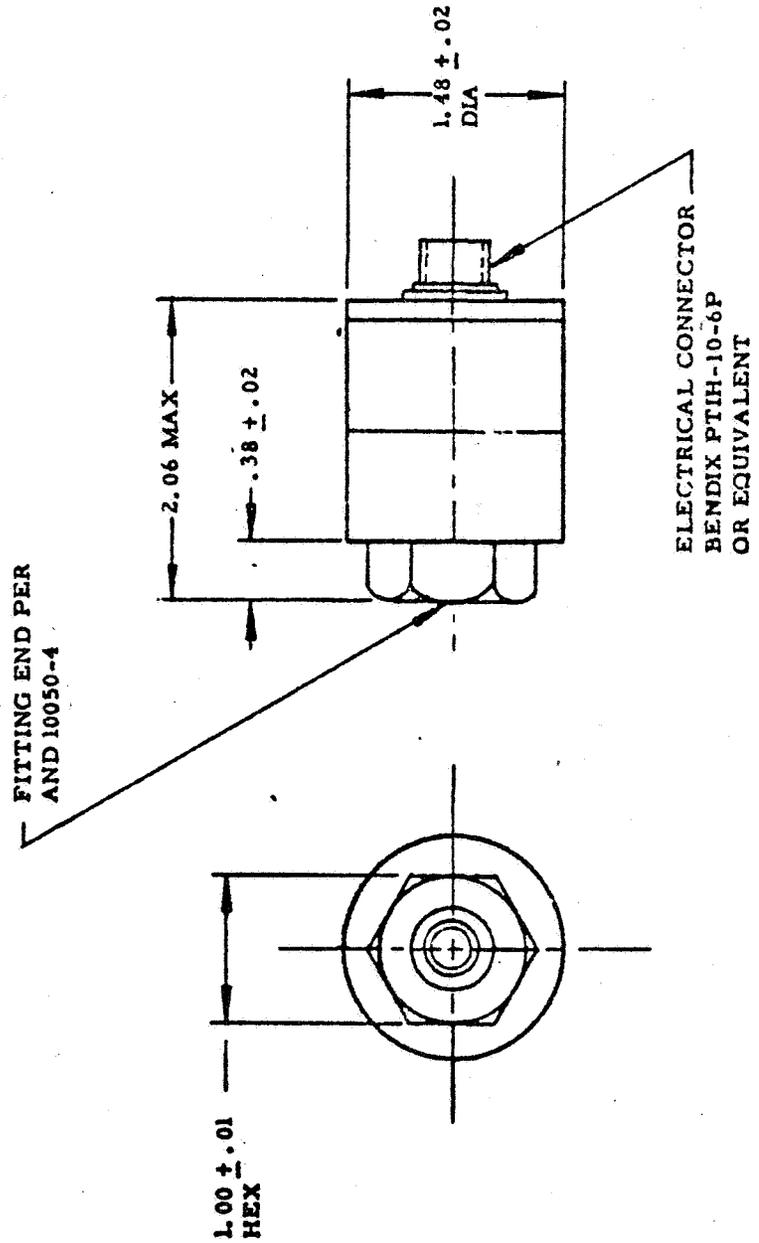


[6]

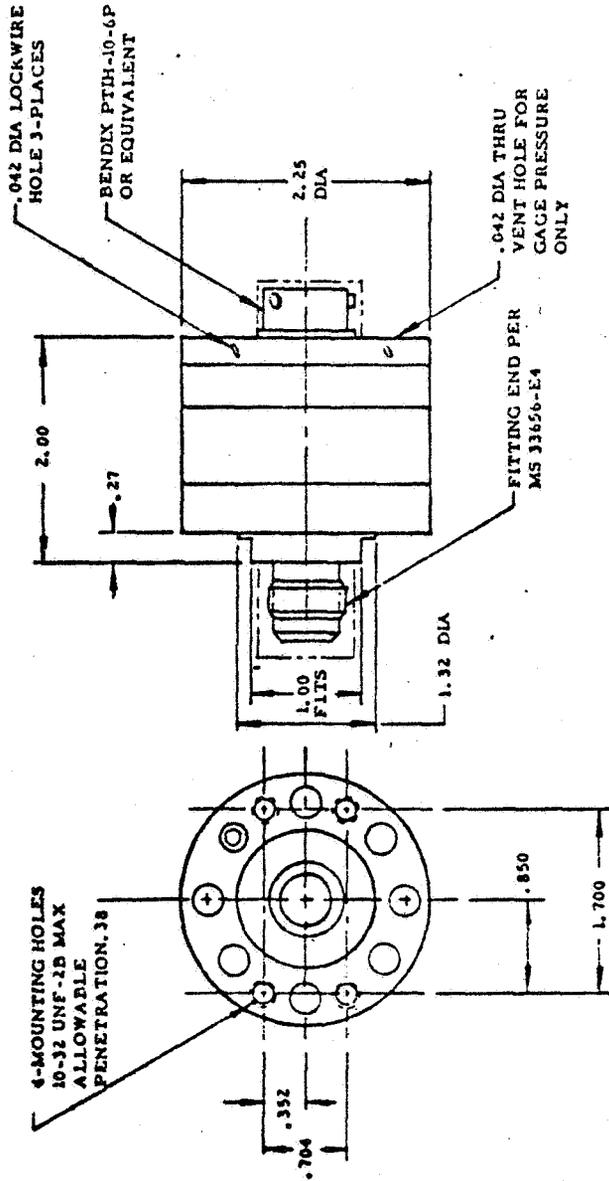
Figure 3.4.1.2-4 Bourns Model 434/534



[7]
Figure 3.4.1.3-1 Model FFB01 Bonded Foil Gage Pressure Transducer
(Absolute and Gage) Scale: Full Size



[7]
Figure 3.4.1.3-2 Model FPB02 Bonded Foil Gage Pressure Transducer
(Absolute and Gage) Scale: Full Size



[7]
Figure 3.4.1.3-3 Foil Gage Pressure Transducer FP803 Scale: Full Size

compensation at the welded joint of the Ni-Span-C aneroid capsule. A special Bourns technique is utilized to achieve this compensation by the application of the welded joint and in the weld material. Other provisions include the selection of good thermal characteristic materials for all primary parts of the sensing assembly. The pressure media cavity is constructed of 304 SS and Ni-Span-C.

3.4.1.3 Dynasciences Corporation [7]

Series FPB 01, 02 and 03 transducers are bonded foil gage instruments with a flat diaphragm as the force summing device coupled to a miniature bending beam. A pair of gages are attached to either side of the bending beam in a fully active Wheatstone bridge configuration. Diaphragm and case are machined as integral parts from 17-4 PH stainless steel. Pressure, applied to the diaphragm, is transmitted directly to the beam and induces displacement resulting in a proportional change in output voltage. The short direct metal path from diaphragm to bending beam provides a low mass, high spring rate system for minimizing acceleration response and a rapid temperature stabilization for minimizing thermal shock and temperature errors. Gages are utilized which compensate for modulus changes, thus improving stability by minimizing compensation network.

Figures 3.4.1.3-1 through 3.4.1.3-3 describe the outline configurations of these instruments.

3.4.1.4 Genisco Technology Corporation [8]

Genisco advertises eight model numbers operable to the cryogenic temperature ranges. All of the instruments employ the bonded strain gage principle. Two basic design approaches are utilized for the cryogenic sensors. Model numbers PB419, PB513, PB519, PB531, PB535, PB536 and PB923 employ a miniature cantilever bending beam design. The cantilever beam is a miniature beam which is part of the diaphragm assembly. Four metal foil strain gages are bonded to the stress concentration areas of the beam to form a fully active, four-arm symmetrical Wheatstone bridge. An overload stop design permits the transducer to withstand overpressures up to 30 times without permanent damage. Model number IBAL03 is a bonded strain gage unit with the foil gages bonded to the back of the diaphragm. Four strain gages, two oriented radially and two circumferentially, are bonded on a single piece of backing material. Pressure applied to one side of the diaphragm deflects the diaphragm and transmits this deflection to the gages bonded to the opposite side. In both designs deflection of the diaphragm provides linear output voltage proportional to the applied pressure and excitation voltage.

All of the transducers are designed with threaded pneumatic fittings and constructed from 17-4PH stainless steel. Instruments are available in ranges from 0 to 15 through 0 to 10,000 psia, psig and psis ranges.

Outline configurations are provided in the following figures. Not all of the part numbers are represented with drawings.

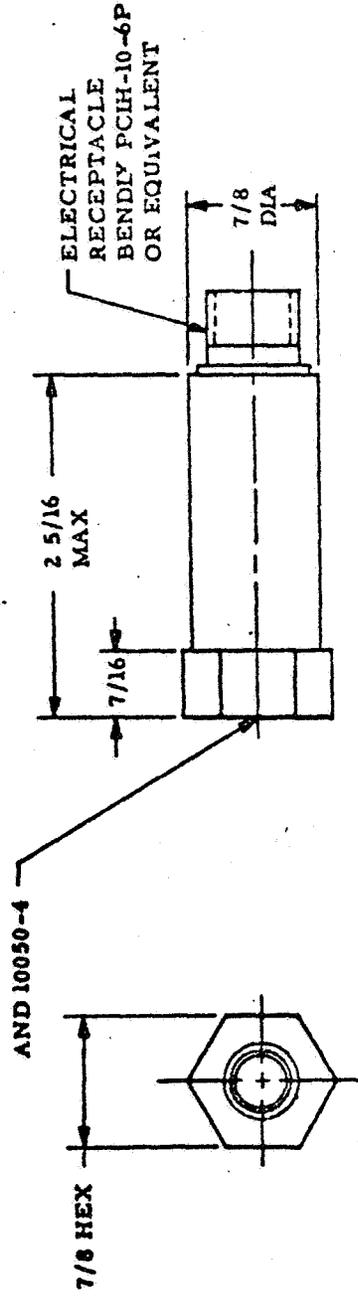


Figure 3.4.1.4-1 (B) Genisco Model 1BA 103 Pressure Transducer Scale: Full Size

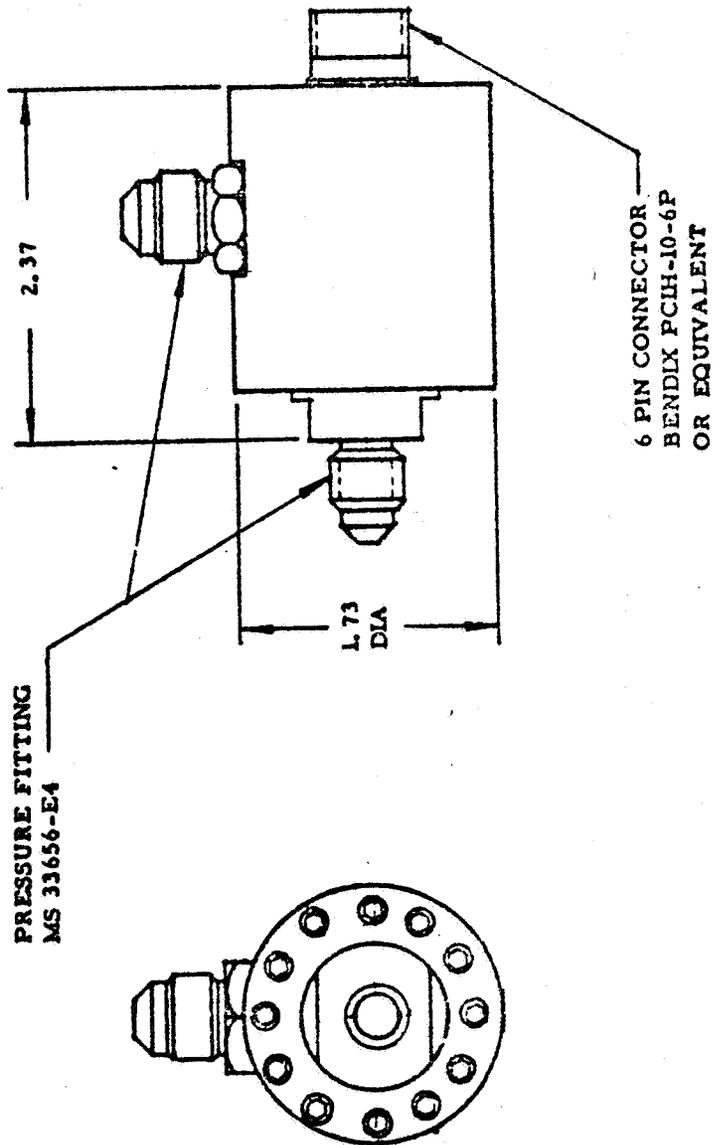


Figure 3.4.1.4-2 [B] Genisco Model PB419 Pressure Transducer Scale: Full Size

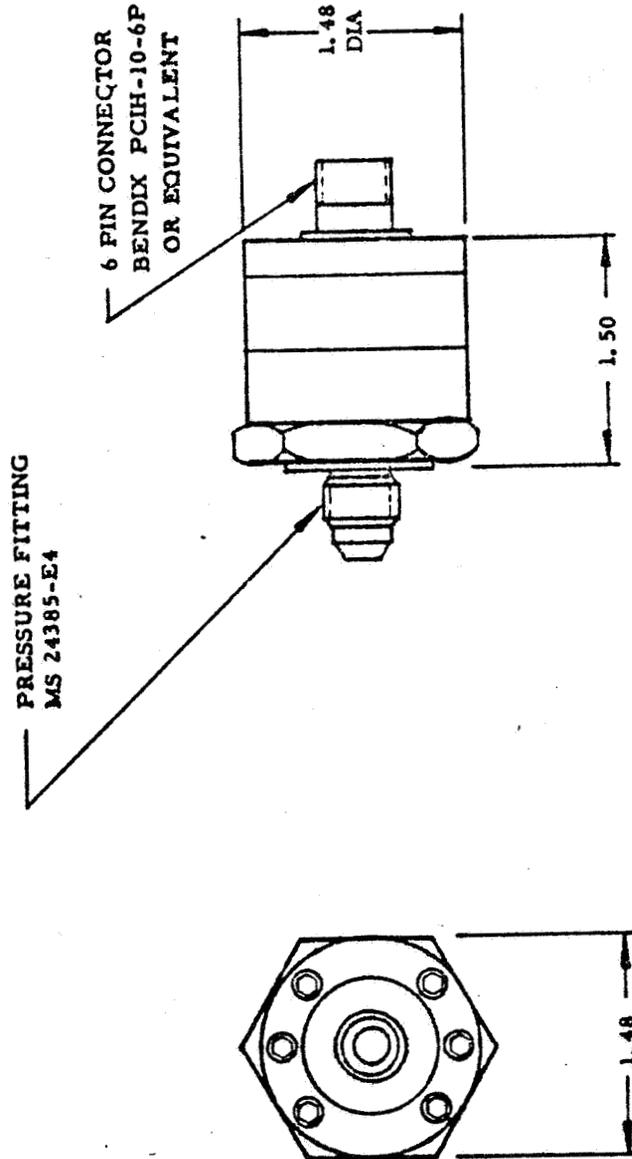


Figure 3.4.1.4-3 [B] Genisco Model PB519 Pressure Transducer Scale: Full Size

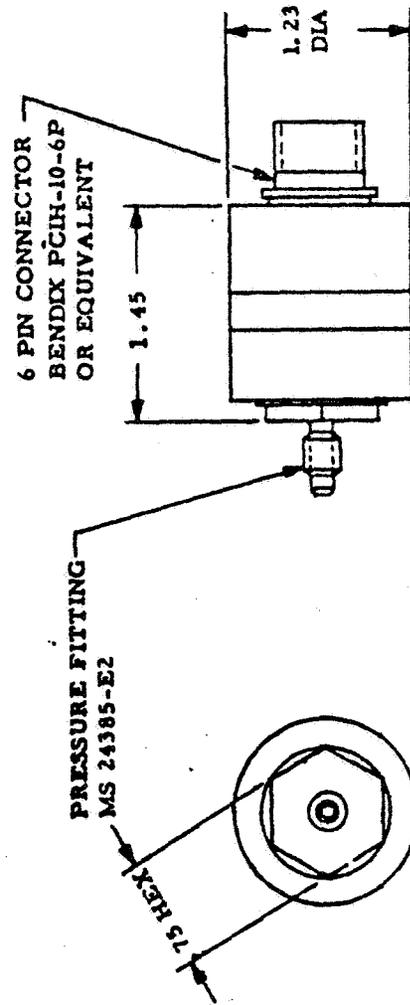


Figure 3.4.1.4-4(a) Genisco Model PB531 Pressure Transducer Scale: Full Size

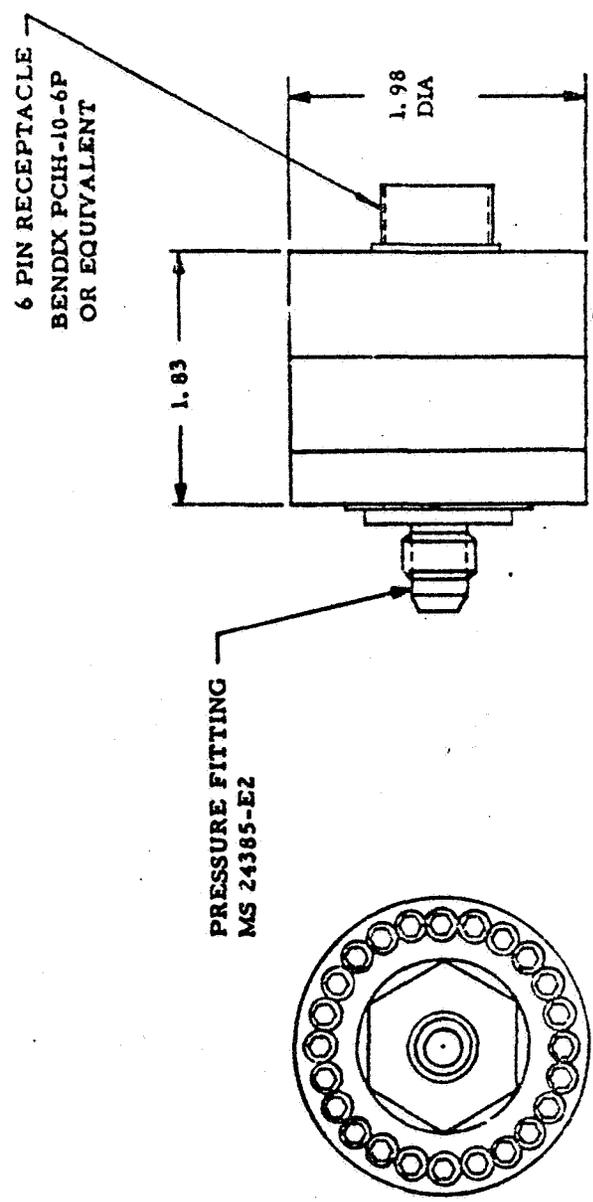


Figure 3.4.1.4-5(a) Genisco Model PB923 Pressure Transducer
Scale: Full Size



3.4.1.5 Kistler^[9]

Series 601, 603 and 606 quartz crystal piezoelectric pressure transducers are dynamic measuring instruments which convert applied pressures to electrical charge signals. Pressure ranges are available from 0 to 30, 100, 300 and up to 10,000 psi. The instruments are characterized by fast response and are useful primarily for measuring dynamic conditions. Ideal applications include the measurement of shockwaves, blasts, explosions, and any pneumatic pulsations or turbulence. Instruments have operational temperature capabilities between ranges of -450 F to 500 F, -320 F to 400 F, -300 F to 450 F.

The instruments operate on the principal that pressure applied to the diaphragm of the transducer is converted to a force action on the quartz crystal. The stress results in a strain which produces an electric charge on opposite faces of the crystal. In the most sensitive axis, the value of the output is 2.30 picocoulombs per newton where one newton equals 0.225 pounds of force. Quartz transducers possess many unique environmental properties. Quartz does not require thermal compensation because it is completely non-pyroelectric. Transducers are highly resistant to shock and vibration because of the great rigidity and strength of the quartz material.

Instruments are capable of withstanding shock and vibration levels in the thousands of g's.

Diaphragms and joints are heli-arc welded for strength and hermetic sealing. Diaphragms are typically constructed from 316 stainless steel. The threaded body for model 606 is constructed from type 304 stainless steel and 17-1 for the higher pressure model series 601 and 603.

The piezoelectric effect of quartz is constant, but the sensitivity of transducers will vary from each other as a function of the number of plates connected in series and with the effective area of the diaphragm. Transducers are individually calibrated for sensitivity in picocoulombs per psi. The attached tables list some current Kistler pressure transducers with their nominal sensitivity values as well as other performance features. The figures show a typical transducer internal design and external configuration.

3.4.1.6 MB Electronics^[11]

Series 172 are bonded strain gage pressure transducers designed for use in a cryogenic environment. Transducers are offered in three reference pressure types, PSIG "gage," PSIA "absolute," and PSIS "sealed." For PSIG transducers, zero reference pressure is ambient atmospheric pressure; for PSIA types, zero reference pressure is absolute zero pressure; while for PSIS units, zero reference pressure is 14.7 psia. The Series 172 instruments are capable of meeting all performance specifications without prior exercising. Instruments may be operated for extended periods of time at the specified maximum voltage of 20 volts ac or dc without resultant permanent change in performance specifications. The units are designed for operation under high levels of shock, sine and random vibration up to 1.0 g²/Hz over the frequency spectrum of 0 to 2000 Hz in any axis.

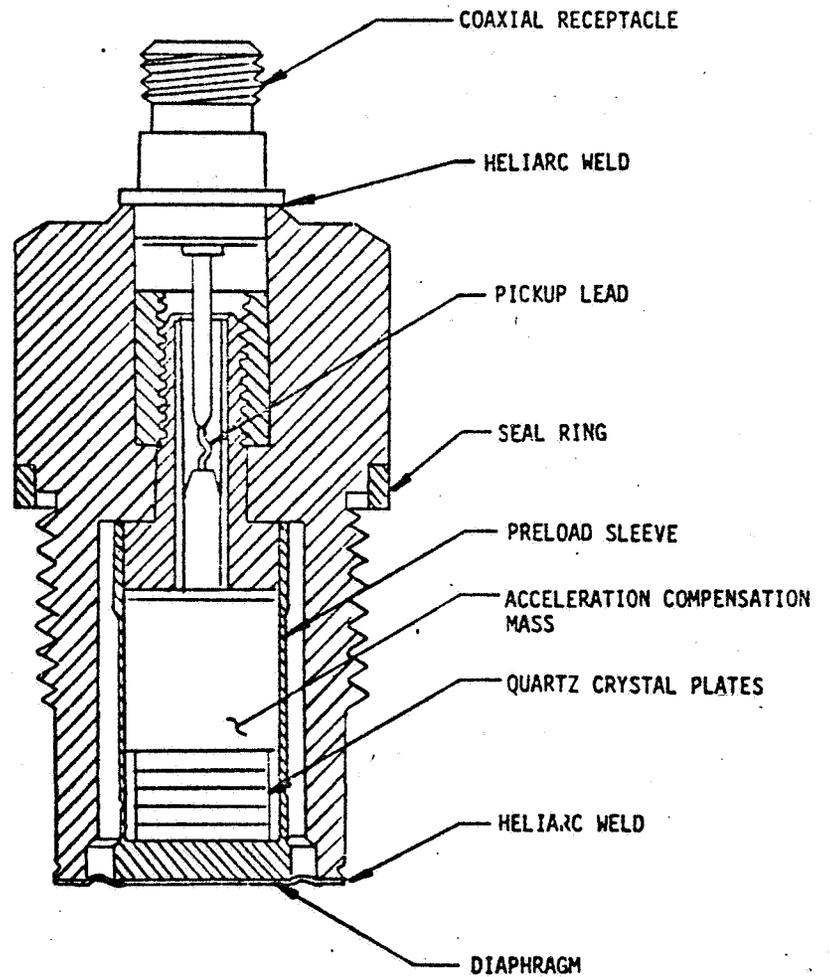


Figure 3.4.1.5-1⁽⁹⁾ Kistler Series Typical Internal Design

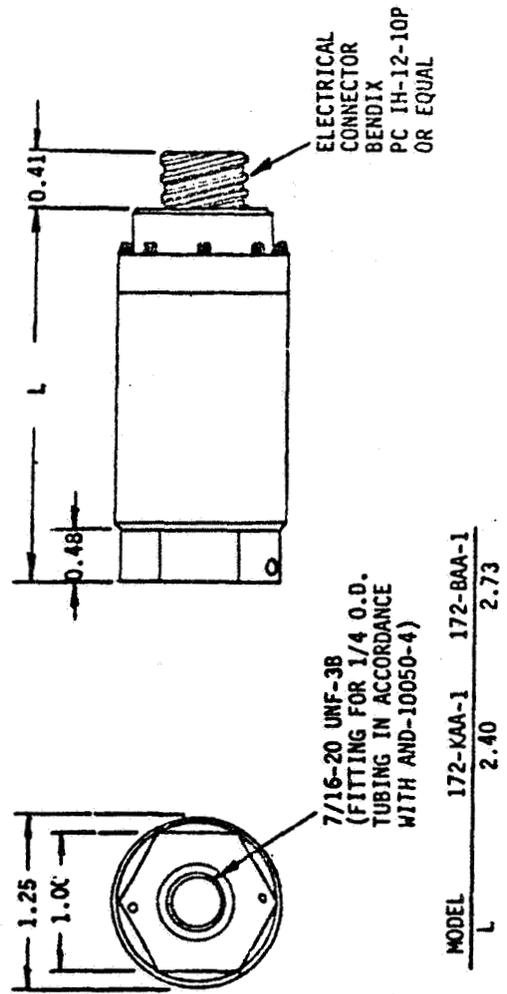


Figure 3.4.1.6-1 MB Electronics Series 172

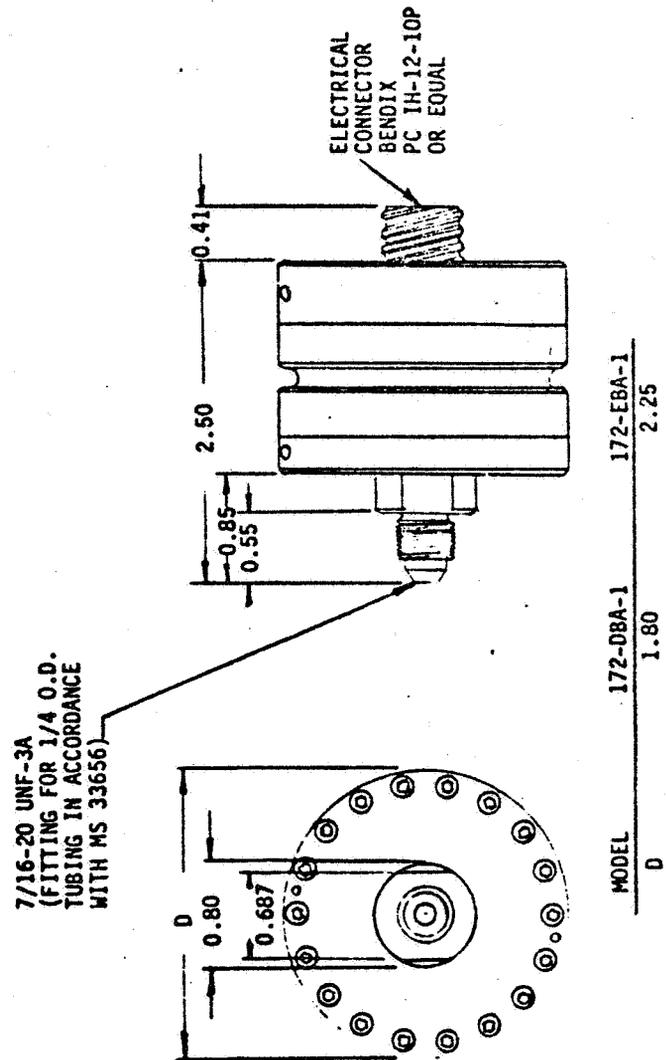


Figure 3.4.1.6-2 MB Electronics Series 172



The body and diaphragm of the transducers are integral; machined from a solid piece of 17-4 PH stainless steel. The design employs a cantilever-beam sensing element using bonded foil strain gages in a four active-arm Wheatstone bridge. Diaphragms are designed up to 0.060 inch thick and thus are not displaced more than a fraction of its thickness to optimize linearity, hysteresis and high repeatability.

The body-diaphragm and all major external parts of transducers are made of 17-4 PH stainless steel. Pure nickel gaskets are used between the pressure head and body on pressure ranges of 100 psi and below. Teflon covered stainless steel O-rings are used on the ranges of 150 to 1000 psi while no sealing devices are used on ranges of 1500 psi and above. Stainless steel connectors are available on special order. In ranges of 2000 psi and above, the transducer diaphragms can withstand over 30,000 psi. The transducers can be used safely in systems that must be vacuum purged, and can be used where shock wave fronts approaching at 90 degrees induce sudden negative pressures. Transducers are designed with no sharp corners or hidden pockets for easy cleaning for LOX and other special aerospace applications. On ranges 1500 psi and up, the entire pressure cavity is accessible without dismantling. On ranges below 1500 psi, the pressure head can be removed to expose the diaphragm.

Transducer outline dimensions are provided in Figures 3.4.1.6-1 and 3.4.1.6-2.

3.4.1.7 Stratham Instruments, Inc. [12]

The Stratham Model PA 822 pressure transducer is a relatively new transducer which utilizes vacuum-deposited thin film strain gages for the sensing element. The transducer is designed with a flat diaphragm whose deflection as a function of applied pressure is transmitted to a double cantilever beam by a linkage pin. Strain gages are vacuum-deposited on the beam in a full bridge configuration so that the deflection causes tensile strain in two gages and compression in the other two gages of the bridge. With excitation voltage applied, the change in bridge balance produces an output voltage proportional to the pressure applied to the diaphragm. Transducers are designed for a typical output of 3 millivolts per volt of excitation.

The Model PA 822 is designed with a threaded pressure fitting fabricated from 17-4 stainless steel. The undercut detail shown in the drawing is designed for mechanical and thermal isolation of the transducer from its mounting surface.

The pressure fitting, diaphragm, linkage pin, frame and beam are electron beam welded to form the sensor mechanism. To obtain a match of temperature coefficient of expansion, the sensor mechanism components are fabricated from the same material 17-4. The vacuum side of the transducer case is electron beam welded to the sensor assembly. Electrical connections are made by micro-circuit welding gold leads to the deposited pads and routing the leads through the hollow fused pins in the vacuum case. The hollow pins are brazed closed and vacuum is pulled on the vacuum case. The vacuum seal is accomplished by an electron beam welded ball seal. The bridge is contained in the hermetically sealed vacuum compartment. Temperature compensation and balance resistors are installed behind the vacuum case. Typically the resistor

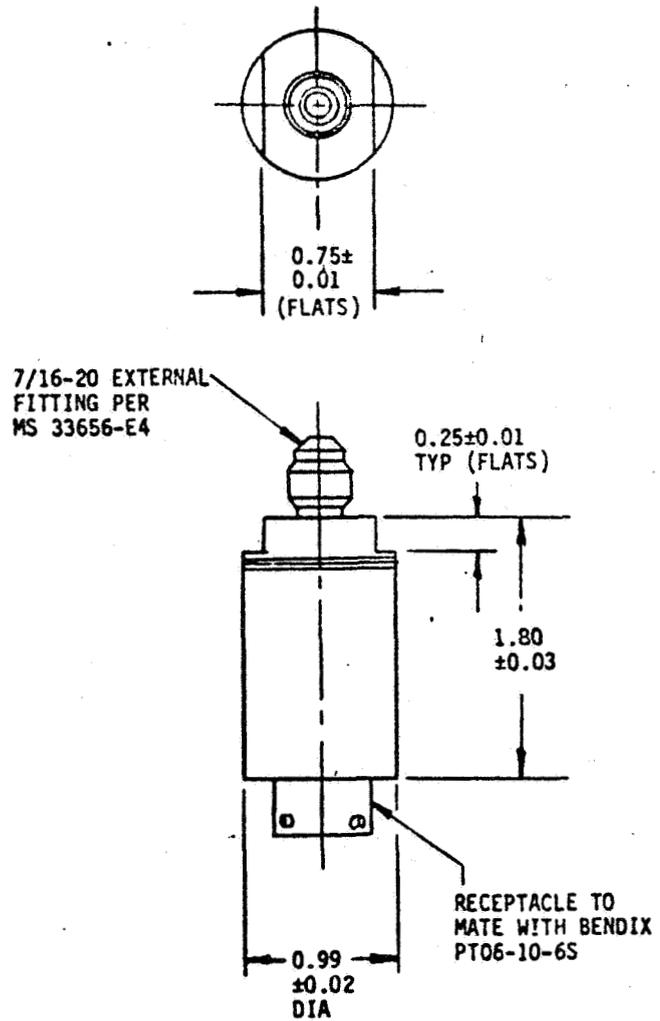


Figure 3.4.1.7-1 [2] Satham Instruments Model PA - 822 - 1M

Table 3.4-1 Tabulation of Performance and Physical
(Sheet 1 of 2)

MANUFACTURER PART NUMBER	OPERATING PRINCIPLE	MEASUREMENT RANGES)	OVER-RANGE	EXCITATION VOLTAGE OR POWER RATING	NON-LINEARITY % FS	HYSTeresis % FS
BELL & HOWELL TYPE 4-312	UNBONDED STRAIN GAGE WITH FLUSH DIAPHRAGM	0-10 THRU 0-150 psia, psig, & psid ±5 THRU ±50 psid	1.5 FULL SCALE	5 vdc	0.5 1.0	
BELL & HOWELL TYPE 4-313	UNBONDED STRAIN GAGE WITH FLUSH DIAPHRAGM	0-10 THRU 0-5,000 psia, psig & psid ±5 THRU ±50 psid	1.5 FULL SCALE	5 vdc	0.5	
BELL & HOWELL TYPE 4-316	UNBONDED STRAIN GAGE WITH FLUSH DIAPHRAGM	0-10 THRU 0-150 psia, psig & psid ±5 THRU ±50 psid	1.5 FULL SCALE	5 vdc	0.5 1.0	
BELL & HOWELL TYPE 4-317	UNBONDED STRAIN GAGE WITH FLUSH DIAPHRAGM	0-50 THRU 0-5,000 psia, psig & psid	1.5 FULL SCALE	5 vdc	0.5 1.0	
BELL & HOWELL TYPE 4-356	UNBONDED STRAIN GAGE WITH PRESSURE PORT	0-10 THRU 0-10,000 psia & psig	2.0 to 2.5 FULL SCALE	10 vdc	0.15 0.5	
BELL & HOWELL TYPE 4-356	UNBONDED STRAIN GAGE WITH PRESSURE PORT	0-10 THRU 0-5,000 psia & psig	2.0 FULL SCALE	10 vdc	0.25	
BELL & HOWELL TYPE 4-361	UNBONDED STRAIN GAGE WITH PRESSURE PORT	0-100 THRU 0-5,000 psia & psig	1.5 FULL SCALE	10 vdc	0.75	
BOURNS MODEL 43M534	POTENTIOMETRIC WITH CORRUGATED DIAPHRAGM	0-1 THRU 0-5 psia, psig & psid	15 psia	1.0 WATT AT 165 F		
BOURNS MODEL 441	POTENTIOMETRIC WITH CORRUGATED DIAPHRAGM	0-5 THRU 0-450 psia	15 to 475 psia	1.0 WATT AT 165 F		
DYNASCENCES SERIES FPB017P002	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-25 THRU 0-5,000 psia or psig	10 x FULL SCALE or 15,000 psi	10 vdc or ac	0.20	0.20
DYNASCENCES SERIES FPB00	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-25 THRU 0-6,000 psia or psig	10 x FULL SCALE or 15,000 psi	10 vdc or ac	0.20	0.15
GENISCO MODEL PG 419	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	50 THRU 1,000 psid	5 x FULL SCALE	10 vdc or ac	0.5	
GENISCO MODEL 913A-34	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-25 THRU 0-5,000 psia, psig or psid	15 x FULL SCALE	10 vdc or ac	0.5	

al Features for Candidate Transducers

NON REPEATABILITY % FS	ZERO POINT OUTPUT % FS	RESOLUTION % FS	FULL SCALE OUTPUT	STATIC ERROR BAND % FS	TEMPERATURE RANGE	TEMPERATURE EFFECTS	WEIGHT SIZE
0.1	10	1%	20 mv 10 mv		-320 to 300 F OPER. -65 to 250 F COMP.	TZS = 0.01%/FULL SCALE/°F TSS = 0.01%/FULL SCALE/°F	13 GRAMS (m41) 10 GRAMS (m16 & 4) 0.625 dia x 0.940 Lg.
0.1	10	1%	20 mv 10 mv		-320 to 300 F OPER. -65 to 250 F COMP.	TZS = 0.012%/FULL SCALE/°F TSS = 0.012%/FULL SCALE/°F	27 GRAMS (m41) 25 GRAMS (m16 & 4) 0.750 dia x 0.90 Lg.
0.1	20	1%	20 mv 10 mv		-320 to 650 F OPER. 75 to 600 COMP.	TZS = 0.01%/FULL SCALE/°F TSS = 0.01%/FULL SCALE/°F	37 GRAMS (m41 & 4) 40 GRAMS (m40) 0.625 x 0.910 Lg.
0.1	20	1%	20 mv		-320 to 650 F OPER. 75 to 600 F COMP.	TZS = 0.01%/FULL SCALE/°F TSS = 0.01%/FULL SCALE/°F	34 GRAMS (m41 & 4) 30 GRAMS (m40) 0.750 dia x 0.96 Lg.
0.1	5	1%	40 mv		-320 to 300 F OPER. -65 to 250 F COMP.	TZS = 0.01%/FULL SCALE/°F TSS = 0.01%/FULL SCALE/°F	4 oz. 0.875 dia x 2.125 Lg.
0.1	5	1%	40 mv		-65 to 300 F OPER. -65 to 250 F COMP. -320 to 77 F COMP.	TZS = 0.007%/FULL SCALE/°F TSS = 0.007%/FULL SCALE/°F	2.5 oz. 0.875 dia x 1.30 Lg.
0.1	10	1%	40 mv		-420 to 700 F OPER. 77 to 600 F COMP. -320 to 77 F COMP.	TZS = 0.01%/FULL SCALE/°F TSS = 0.01%/FULL SCALE/°F	9 oz. 1.0 x 2.0 x 2.0
		0.3		1.5 to 2.0	-320 F OPER. -65 to 145 F COMP.	±2.5 to 3.5% FULL SCALE OVER COMP. RANGE	9 oz. 1.0 x 2.0 x 2.0
		0.3		1.2 to 1.5	-320 F OPER. -65 to 200 F COMP.	±2.2 to 2.5% FULL SCALE OVER COMP. RANGE	2.5 oz. 1.0 dia x 1.0 Lg.
0.05	2.0	1%	3 mV		-320 F OPER. -65 to 250 F COMP.	TZS = 0.01%/FULL SCALE/°F TSS = 0.01%/°F	12 oz. min 1.50 dia x 2.00 Lg.
0.05	2.0	1%	3 mV		-320 F OPER. -65 to 250 F COMP.	TZS = 0.01%/FULL SCALE/°F TSS = 0.005%/FULL SCALE/°F	12 oz. min 1.70 dia x 2.00 Lg.
0.1			3 mV		-425 to 275 F OPER. -65 to 250 F COMP.	TZS = 0.01%/FULL SCALE/°F TSS = 0.01%/FULL SCALE/°F	17 oz. 1.73 dia x 2.37 Lg.
			3 mV	0.35	-425 to 300 F OPER. 32 to 400 F COMP.		20 oz. 1.8 dia x 2.0 Lg.

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Table 3.4-1 Tabulation of Performance and Physical Features
(Sheet 2 of 2)

MANUFACTURER PART NUMBER	OPERATING PRINCIPLE	MEASUREMENT RANGE(S)	OVER-RANGE	EXCITATION VOLTAGE OR POWER RATING	NON LINEARITY % FS	HYSTERESIS % FS	NON REPEATABILITY % FS	2 σ
GENISCO MODEL 513-30	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-50 THRU 0-5,000 psia, psig or psis	10 x FULL SCALE	10 vdc or ac	-	0.15	0.1	-
GENISCO MODEL 531	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-15 THRU 0-5,000 psia, psig or psis	3 x FULL SCALE	10 vdc or ac	0.25	-	0.1	-
GENISCO MODEL 531-30	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-25 THRU 0-5,000 psia, psig or psis	1.5 x FULL SCALE	10 vdc or ac	-	-	-	-
GENISCO MODEL 536	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-25 THRU 0-5,000 psia, psig or psis	1.5 x FULL SCALE	10 vdc or ac	-	-	-	-
GENISCO MODEL 535	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-20 THRU 0-4,000 psia, psig or psis	3 x FULL SCALE	10 vdc or ac	0.5	-	0.1	-
GENISCO MODEL 923	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-15 THRU 0-5,000 psia, psig or psis	10 x FULL SCALE	10 vdc or ac	0.15	-	0.1	-
GENISCO MODEL 923-20	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-20 THRU 0-4,000 psia, psig or psis	2 x FULL SCALE	10 vdc or ac	0.75	-	0.08	-
GENISCO MODEL 923-30	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-15 THRU 0-10,000 psia, psig or psis	10 x FULL SCALE	10 vdc or ac	0.3	-	0.1	-
GENISCO MODEL 18 100	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-200 THRU 0-9,000 psia, psig or psis	1.5 x FULL SCALE	10 vdc or ac	0.5	-	0.25	-
GENISCO MODEL PB 519	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-15 THRU 0-5,000 psia, psig or psis	5 x FULL SCALE	10 vdc or ac	0.25	0.15	0.1	-
GENISCO MODEL 5195-4	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-15 THRU 0-3,000 psia, psig or psis	5 x FULL SCALE	0.3 vdc or ac	1.0	-	0.1	-
KISTLER MODEL 601A 1	PIEZOELECTRIC	to 3000 psi	5000 psi	-	1.0	-	-	-
MODEL 601J	PIEZOELECTRIC	to 100 psi	1000 psi	-	1.0	-	-	-
MODEL 601A	PIEZOELECTRIC	to 3000 psi	5000 psi	-	1.0	-	-	-
MODEL 601H	PIEZOELECTRIC	to 15000 psi	20000 psi	-	1.0	-	-	-
MODEL 601I	PIEZOELECTRIC	to 800 psi	1000 psi	-	1.0	-	-	-
MODEL 601A	PIEZOELECTRIC	to 3000 psi	5000 psi	-	1.0	-	-	-
MODEL 601H	PIEZOELECTRIC	to 15000 psi	20000 psi	-	1.0	-	-	-
MODEL 601A	PIEZOELECTRIC	to 3000 psi	5000 psi	-	1.0	-	-	-
MODEL 601H	PIEZOELECTRIC	to 15000 psi	20000 psi	-	1.0	-	-	-
MB ELECTRONICS MODEL 172-KAA-1	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-1500 thru 0-10,000 psia, psig or psis	3 x FULL SCALE OR 20000 psi	10 vdc or ac	0.25	0.15	0.05	-
MB ELECTRONICS MODEL 172-BAA-1	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-150 thru 0-1000 psia, psig or psis	3 x FULL SCALE	10 vdc or ac	0.25	0.15	0.05	-
MB ELECTRONICS MODEL 172-DBA-1	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-25 thru 0-100 psia, psig or psis	3 x FULL SCALE	10 vdc or ac	0.25	0.15	0.05	-
MB ELECTRONICS MODEL 172-EBA-1	BONDED FOIL STRAIN GAGE FLAT DIAPHRAGM	0-10 thru 0-100 0-15 thru 0-20 psia, psig or psis	3 x FULL SCALE	10 vdc or ac	0.25	0.15	0.05	-
STATHEM MODEL PAB2	THIN FILM STRAIN GAGE FLAT DIAPHRAGM	0-15 thru 0-5000 psia	2 x FULL SCALE THRU 500 psi RANGE 1.5 x FULL SCALE 1000 THRU 5000 psi RANGE	10 vdc or ac	0.3	0.3	-	-

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Features for Candidate Transducers

ZERO PRESSURE OUTPUT P.P.S.O.	RESOLUTION P.P.S.O.	FULL SCALE OUTPUT	STATIC FREQUENCY P.P.S.O.	TEMPERATURE RANGE	TEMPERATURE EFFECTS	WEIGHT & SIZE
		3mv/v		-425 to 320 F OPER -320 to 250 F COMP.	TZS = 0.002%/FULL SCALE/°F TSS = 0.002%/FULL SCALE/°F	18 oz. 1.8 dia x 2.0 lg.
		3mv/v		-320 to 300 F OPER -45 to 250 F COMP.	TZS = 0.01%/FULL SCALE/°F TSS = 0.01%/FULL SCALE/°F	5 oz. 1.25 dia x 1.5 lg.
		3mv/v	0.5	-320 to 140 F OPER -40 to 140 F COMP.		6.5 oz. 1.25 dia x 1.5 lg.
		4mv/v		-320 to 500 F OPER -700 to 300 F COMP.		8 oz. 1.75 dia x .5 lg.
		4mv/v		-320 to 250 F OPER 25 to 200 F COMP.	TZS = 0.002%/FULL SCALE/°F TSS = 0.002%/FULL SCALE/°F	12 oz. 1.5 dia x 1.5 lg.
		3mv/v		-425 to 275 F OPER -45 to 250 F COMP.	TZS = 0.002%/FULL SCALE/°F TSS = 0.002%/FULL SCALE/°F	20 oz. 1.90 dia x 1.90 lg.
		3mv/v		-450 to 300 F OPER -320 to 250 F COMP.	TZS = 0.002%/FULL SCALE/°F TSS = 0.002%/FULL SCALE/°F	20 oz. 1.90 dia x 1.90 lg.
		3mv/v		-425 to 275 F OPER -320 to 165 F COMP.	TZS = 0.002%/FULL SCALE/°F TSS = 0.002%/FULL SCALE/°F	20 oz. 1.90 dia x 1.90 lg.
		3mv/v		-425 to 290 F OPER 0 to 200 F COMP.	TZS = 0.02%/FULL SCALE/°F TSS = 0	3 oz. .75 dia x 1.5 lg.
		3mv/v		-425 to 300 F OPER -45 to 250 F COMP.	TZS = 0.01%/FULL SCALE/°F TSS = 0.01%/FULL SCALE/°F	9 oz. 1.5 dia x 1.5 lg.
		3mv/v		-425 to 250 F OPER -320 to 165 F COMP.	TZS = 0.02%/FULL SCALE/°F TSS = 0.02%/FULL SCALE/°F	9 oz. 1.5 dia x 1.5 lg.
	3.1 psi			-320 F to +400 F OPER.	0.02% FULL SCALE/F	2.25 gms 0.25 dia x 0.6 lg.
	0.1 psi			-320 F to +400 F OPER.	0.02% FULL SCALE/F	
	0.1 psi			-450 F to +500 F OPER.	0.01% FULL SCALE/F	0.08 oz.
	1.0 psi			-450 F to +500 F OPER.	0.01% FULL SCALE/F	.25 dia x 0.6 lg.
	0.1 psi			-450 F to +500 F OPER.	0.01% FULL SCALE/F	
	0.01 psi			-450 F to +500 F OPER.	0.02% FULL SCALE/F	1.7 gms
	0.01 psi			-450 F to +500 F OPER.	0.02% FULL SCALE/F	
	0.005 psi			-350 F to +450 F OPER.	0.02% FULL SCALE/F	22 gms
	0.005 psi			-350 F to +450 F OPER.	0.02% FULL SCALE/F	0.45 dia x 1.25 lg.
1.0		1.0 mv/v		-452 F to +250 F OPER. -320 F to +77 F COMP.	TZS: 1.0% FULL SCALE MAX/100F TSS: 0.5% FULL SCALE MAX/100F	7.5 oz. 1.25 dia x 2.0 lg.
1.0		1.0 mv/v		-452 F to +250 F OPER. -320 F to +77 F COMP.	TZS: 1.0 FULL SCALE MAX/100F TSS: 0.5% FULL SCALE MAX/100F	8.1 oz. 1.25 dia x 1.5 lg.
1.0		1.0 mv/v		-452 F to +250 F OPER. -320 F to +77 F COMP.	TZS: 1.0 FULL SCALE MAX/100F TSS: 0.5% FULL SCALE MAX/100F	7.5 oz. 1.00 dia x 1.95 lg.
1.0		1.0 mv/v		-452 F to +250 F OPER. -320 F to +77 F COMP.	TZS: 1.0% FULL SCALE MAX/100F TSS: 0.5% F.S. MAX/100F	18 oz. 2.25 dia x 1.95 lg.
2.0	1NF	1.0 mv/v		-320 F to +40 F COMP.	TAS: 0.01% FULL SCALE/F TSS: 0.01% FULL SCALE/F	4.5 oz. 1.0 dia x 1.00 lg.

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networks are potted to provide protection from vibration and shock. The outer case and hermetically sealed connector are electron beam welded for a completely hermetic sealed transducer.

The PA 822 transducers are temperature compensated for operation over the range of -320 F to 80 F to offset errors from the temperature coefficient of resistance of the gage material, gage matching, and the match of coefficient of expansion of the sensing mechanism structure. Gage matching can be accomplished closely since the thin film process is applied simultaneously to all four gages with precisely controlled deposition masks. Sensing mechanism structural components are all fabricated from the same material to minimize coefficient of expansion errors. Zero shift and sensitivity change are compensated by adding resistors with the appropriate temperature coefficients of resistance to the bridge circuit.

Transducer details are provided in the following figures.

Table 3.4-1 provides a tabulation of some performance and physical design features. While any one or a number of transducer operational or design features could be key to the selection of a specific transducer, the following are considered some of the more important. The terminology used in the tabulation is in keeping with the Instrument Society of America transducer terminologies.

OPERATING PRINCIPLE: The nature of the sensing technique and the transduction principle necessary to sense the measurand and produce an output signal.

MEASURAND RANGE: Minimum and maximum values of the measurand

OVERRANGE: The maximum magnitude of measurand that can be applied to a transducer without causing a change in performance beyond specified tolerances (expressed as percent of full-scale measurand).

EXCITATION: The nature and magnitude of all external energy required for proper transducer operation; excluding the measurand.

NON-LINEARITY (Endpoint Method): The deviation of actual output of the transducer from a straight line between zero pressure and rated pressure outputs during one complete pressurization cycle. Expressed as a percentage of full-scale output.

HYSTERESIS: The difference in output at any given pressure value within the transducer range when the value is approached first with increasing and then with decreasing pressure.

NON REPEATABILITY: The inability of the transducer to produce the same output, under identical environmental conditions, during three consecutively repeated pressurization cycles. Expressed as a percentage of full-scale output.

RESOLUTION: The smallest change of measurand that produces a recognizable change in output expressed as percent of full-scale measurand.

FULL-SCALE OUTPUT: The change in output between zero pressure and rated pressure, expressed in millivolts output per volt input.

COMPENSATED TEMPERATURE: The range of temperature over which the transducer is compensated so that thermal sensitivity shift and thermal zero shift will not exceed the specified amount.

SENSITIVITY SHIFT WITH TEMPERATURE: The change in sensitivity caused by a specified change in ambient temperature within the compensated temperature range. Expressed as a percentage of reading per 100 F.

ZERO PRESSURE OUTPUT SHIFT WITH TEMPERATURE: The change in the zero pressure output of the transducer with a change in temperature. Expressed as a percentage of full-scale output per 100 F.

MAXIMUM SAFE EXPOSURE TEMPERATURE: The maximum temperature to which the transducer may be exposed without a permanent change in performance characteristics.

3.4.2 Trade Evaluation of Designs

The transducers identified as capable of operating in a cryogenic application are all split package designs. Transducers with integral electronics are available for cryogenic applications; however, the limited temperature capability of the electronics necessitates a remote transducer installation and/or thermal protection provisions. This statement assumes a transducer temperature operating environment within cryogenic ranges. Generally, instruments with these design features are available by special order only.

Transducers operating with a thermal control provision, such as an internal heater, or protected by installation in a temperature control container are capable of a high degree of measurement accuracy, generally better than any split package design under extremes of temperature. There are, however, a number of serious limitations.

- a. The units require a heater which becomes a source of heat leak into the cryogenic system. This limits the use of these transducers to a remote installation only.
- b. The unit size is generally larger due to the electronics and heater provisions. The larger transducer size requires bracketry for installation.
- c. In applications where large numbers of measurements are required to operate over long durations, electrical power requirements become a serious trade consideration and electrical power limitations and safety consideration may dictate the operation of units without heaters.



Because of the limitations identified, transducers with integral electronics are useful only for remotely installed applications and where the tradeoff of high electrical power for heaters is considered justified in order to achieve the accuracy level of these units.

All of the instruments identified as candidates for this investigation are split package designs which are available in a wide range of sizes and weights and differ considerably in operating principle. The principles include strain gage, potentiometric and piezoelectric techniques. As described earlier, the signal output for these instruments differ significantly. Potentiometric units provide high-level outputs, strain gage units operate with low-level outputs and the piezoelectric transducer provides a charge output. These differences are further expanded to include differences in wiring, signal conditioning requirements, and excitation supply voltages. In these areas the potentiometric transducer excels. The unit provides a convenient high-level output either ac or dc as a function of the excitation supply voltage. The common application is to provide a 5 vdc supply for a 0 to 5 vdc signal output. Except for the power supply, no additional modules for signal conditioning is required. Both the strain gage units and the piezoelectric transducer require the use of amplifiers for signal conditioning. The cost of an additional signal conditioning module and installation and wiring provisions as well as the added weight factor rank the strain gage and piezoelectric units lower than the potentiometric unit in this regard.

As far as the sizes and weights of the transducers are concerned, there is a wide variation between manufacturers. The piezoelectric instruments are the smallest and lightest of all the instruments. The unit weight and size factor is an important consideration for cryogenic measurements, especially where the instruments must be installed in the close-coupled configuration. In many cases, the unit weight in conjunction with the high vibration and shock environments prohibit installation of these transducers directly into the pressure ports or bosses without additional support bracketry. For these larger and heavier transducers, a significant convenience and cost savings factor is lost, which is considered one of the advantages of the split package design. The convenience factor results from the easy removal and interchangeability of transducers and the cost factor results from savings in bracketry costs. Since a number of variables are interrelated in determining the feasibility of installing a transducer directly into a port, no definite statements can be made for size and weight ranges for safe installations without brackets. For purposes of this study, an example is cited based on an S-II stage usage where a transducer weighing approximately six ounces was port mounted safely on a feedline. Approximately 40 percent of the transducers discussed in this study weigh less than six ounces. The size of the instrument is also a significant consideration with respect to the influence of the temperature extremes on the sensor. Conclusions by Kinzie and Murphy as described in reference source [15] indicate that heavy, thermally well-protected cavity type transducers have relatively good performance characteristics under certain transient flowing liquid hydrogen applications. Other evidence indicates that a transducer capable of reaching a uniform temperature rapidly is most likely to reach a stabilized output rapidly. Transducers which are capable of exposure to temperature extremes and gradients

with the minimum of stress to the case and to sensing elements is less likely to exhibit large errors. Small transducer size contributes toward this goal by reducing thermal mass and minimizing temperature gradients. In addition, insulating the transducer to maintain a constant temperature is facilitated with small units.

Closely allied to the transducer size consideration is the configuration. All transducers listed in this survey have either a male or female threaded fitting or threaded body except Bell and Howell's models 4-312, 4-313, 4-316 and 4-317. These units have flush diaphragms with a flange seal. Transducers with male or female threaded fittings provide flexibility for inter-changing units, perhaps one range for another or one manufacturer's part for another manufacturer's part (assuming compatible thread size). Some of the units with external threaded fittings are flush diaphragm designs with the body threaded rather than with pneumatic fittings. Transducers of this configuration have definite advantages for monitoring dynamic pressure responses of a cryogenic medium. Transducers of this configuration with the thread size are listed.

<u>Manufacturer/Part Number</u>	<u>Thread Size</u>
Kistler Models 606A and 606L	1/2 - 20

Units with threaded male fittings are:

<u>Manufacturer/Part Number</u>	<u>Thread Size</u>
Bourns Model 441	MS-33656, -E2, 3 or 4
Bourns Model 434/534	MS-33656-E4
Dynasciences FPB01/FPB02	MS-33656-E4
Dynasciences FPB03	MS-33656-E4
MB Electronics Models 172-DBA-1 and EBA-1	MS-33656-E4
Statham Model PA 822	MS-33656-E4
Genisco Technology Corporation	MS-24385-E4
Bell & Howell Series 4-326 4-356 4-361	MS-33656-E4

Units with threaded female fittings are listed below. It should be pointed out that units with female fittings can be converted to male fittings with an adapter.

<u>Manufacturer/Part Number</u>	<u>Threaded Fitting</u>
MB Electronics Model 172-KAA-1 172-EAA-1	7/16 - 20 UNF - 3B per AND-10050-4

Another consideration related to interchangeability is the transducer output impedance, supply voltage and signal output voltage. A tabulation of strain gage designs result in the following breakdown.



<u>Supplier</u>	<u>Excitation Voltage (ac or dc)</u>	<u>Output Impedance (ohms)</u>	<u>Signal Output (mv/v)</u>
Dynasciences	10V	350	3.0
Statham	10V	350	3.0
MB Electronics	10V	350	3.0
Genisco	10V	350	3.0
Bell & Howell	10V	350	3.0 (4-312, 313, 316, 317) 4.0 (4-356, 361)

The candidate strain gage instruments of this study all have standard outputs of 3.0 mv per volt of excitation except the Bell and Howell models 4-356 and 4-361 which have a 4.0 mv per volt output. These electrical commonalities ease interchangeability problems from one manufacturer's part to another. One consideration which should not be overlooked is that differences in the various tolerances will affect the end point values and also the output sensitivity value. Wherever a single amplifier provides signal conditioning for a number of measurements, the use of these transducers may not be suitable due to the variations between instruments.

Transducer shelf life and operational life data have not been identified from this survey. In addition, these characteristics are a function of the cycling rate and operational pressure magnitude and whether the unit is operated at full range or at an intermediate range. Based on an assessment of these component parts, it can be stated that generally all of the candidate transducers are designed for simplicity and of materials without significant deteriorating properties. In the case of absolute units, long-life capabilities are further enhanced by the fact that the sensing mechanism is usually located in the evacuated chamber where corrosive or oxidizing effects are minimized. The structural members associated with the sensing system are all fabricated from high-strength stainless steels and operated at the low end of its endurance limit value. These structural members should not normally be a failure source unless overpressured. The unknown components with respect to life are compensating resistors, strain gage elements, connecting wiring and their junctions and connector elements. In the case of the potentiometric transducer, the wiper and potentiometer are definite elements with limited life. A wide variation exists among units and designs; however, for the purpose of this report, an estimate is made that potentiometric units have a life of approximately 25,000 to 250,000 cycles. This estimate includes performance changes beyond specification limits resulting from wear and wiper/resistance element contamination.

Since data are not available for a statistical analysis or a detail materials and process analysis, no conclusion can be made based on these findings. A statement can be made that the piezoelectric and strain gage units are designed with a minimum of components and complexity which would indicate that failure modes and wear are minimal. In general, all of the candidate units of this investigation are estimated to have good shelf life and operational life.

	MEASURAND RANGE	OPERABLE AND COMPENSATED TEMPERATURE RANGE(S)	TEMPERATURE OPERATIONAL RANGE CAPABILITY	COMBINED TEMPERATURE ERROR OVER COMPENSATED RANGE % FULL SCALE ⁽²⁾	LOWEST COMPENSATED TEMPERATURE CAPABILITY AND ERROR ⁽¹⁾ BASED ON +77° CALIBRATION
BELL & HOWELL TYPE 4-354	0-10 THRU 0-5,000 psia or psig	OPERABLE -45°F to 300°F COMPENSATED -32°F to 77°F	MEETS DESIGN GOALS	0.01	-32°F 3.9%
BELL & HOWELL TYPE 4-361	0-100 THRU 0-5,000 psia or psig	OPERABLE -42°F to 300°F COMPENSATED -32° to 77°	BEST MEETS DESIGN GOALS	0.02	-32°F 7.9%
BOURAS MODEL 441	0-5 THRU 0-450 psia	OPERABLE -32°F COMPENSATED -65 to 220°	LIMITED	0.008 to 0.009	-65° 1.1%
DYNASCENCES SERIES FP80U FP80Z	0-25 THRU 0-5,000 psia or psig	OPERABLE -32°F COMPENSATED -32°	LIMITED	0.02	-32°F 7.9%
GENISCO MODEL 513-39	0-50 THRU 0-5,000 psia, psig or psis	OPERABLE -45°F to 300°F COMPENSATED -32°F to 250°F	MEETS DESIGN GOALS	0.01	-32°F 3.9%
GENISCO MODEL 923-24	0-20 THRU 0-5,000 psia, psig or psis	OPERABLE -45°F to 300°F COMPENSATED -32°F to 250°F	MEETS DESIGN GOALS	0.016	-32°F 6.3%
KISTLER MODEL 881 L	to 300 psi	OPERABLE -45°F to 300°F COMPENSATED -60°F to 500°F	MEETS DESIGN GOALS	0.01	-45°F 5.2%
MB ELECTRONICS MODEL 172-08A-1	0-25 THRU 0-100 psia, psig or psis	OPERABLE -45°F to 250°F COMPENSATED -32°F to 77°	MEETS DESIGN GOALS	2.015	-32°F 5.9%
STATHAM MODEL PA 822	0-15 THRU 0-5,000 psia	OPERABLE -32 to 90° COMPENSATED -32 to 80°	LIMITED	0.02	-32°F 7.9%
(2)	NOTE: THE ERROR SPECIFIED IS STRICTLY BASED ON THE ADVERTISED SENSITIVITY COEFFICIENTS. IN PRACTICE THE ERROR VALUE MAY BE INFLUENCED BY OTHER PERFORMANCE PARAMETERS				
(1)	MAXIMUM PEAK SINUSOIDAL VIBRATION ADVERTISED				
(3)	ESTIMATED BY AUTHOR				
(4)	AS ADVERTISED BY SUPPLIER				
(5)	0 WIRES FOR COMPLETE MEASUREMENT REDUNDANCY				

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TABLE 3.4.2-1
SUMMARY TABLE FOR SELECTED TRANSDUCER
FOR CRYOGENIC APPLICATION

VIBRATION ⁽²⁾ PEAK SINUSOIDAL	SHOCK	OPERATIONAL LIFE DESIGNED MTBF	ELECTRICAL POWER REQUIREMENTS	TRANSDUCER SIZE AND WEIGHT		MEASUREMENT REDUNDANCY PROVISIONS
7g	100g	LONG LIFE EXPECTED	LOW	SMALL LIGHT	4 WIRES	NONE
25g	10g	LONG LIFE EXPECTED	LOW	EXCEEDS 6 OZ.	4 WIRES	NONE
7g	50g	USUALLY LIMITED BY WEAR OF POT; ⁽³⁾ 25K to 250 cycles	LOWEST	SMALL LIGHT	4 WIRES	NONE
-	-	LONG LIFE EXPECTED	LOW	EXCEEDS 6 OZ.	4 WIRES	NONE
42g	-	LONG LIFE EXPECTED (2500 HRS) ⁽⁴⁾	LOW	EXCEEDS 6 OZ.	4 WIRES	NONE
50g	-	LONG LIFE EXPECTED	LOW	EXCEEDS 6 OZ.	4 WIRES	NONE
1500g	1500g	LONG LIFE EXPECTED	LOW	SMALLEST LIGHTEST	4 WIRES	NONE
30g	-	LONG LIFE EXPECTED	LOW	EXCEEDS 6 OZ.	4 WIRES	NONE
-	-	LONG LIFE EXPECTED ⁽⁴⁾	LOW	SMALL LIGHT	4 WIRES ⁽⁵⁾	AVAILABLE

capabilities. Saturn S-II Program experience with strain gage pressure transducers indicate that the instruments are reliable with shelf life estimated at five to ten years or longer.

Vibration capability of representative candidate instruments are listed below:

<u>Supplier/Part Number</u>	<u>Frequency</u>	<u>Displacement or g's</u>	<u>Errors</u>
Bourns	5-25 25-2000	0.5 da 16-35 g's Pk	1.5% FR max
MB Electronics	0-2000	30 g Pk	0.025% FR/g
Bell & Howell	5-2000	35 g Pk	0.03% FR/g
Kistler	Limit not determined	1500 g Pk	0.005 PSI/g

The values above for strain gage units are for ranges to 100 psi. For the potentiometric unit, the range is to 450 psi. From the data above it is clear that the piezoelectric instrument is exceptional with respect to vibration capability. As indicated in the description of piezoelectric instruments, the outstanding vibration characteristics result from the essential lack of moving parts. Two representative strain gage instruments, a bonded foil gage unit and an unbonded strain gage instrument exhibit approximately similar capability. The potentiometric unit is most susceptible. These results are in keeping with the inherent design characteristics of these instruments. Instruments with internal designs having mechanical linkages and deflection members are more sensitive to acceleration forces.

Table 3.4.2-1 summarizes some of the more important performance features of selected transducers from each manufacturer which appears to have the best cryogenic performance capability and which are available in pressure ranges most likely required for a cryogenic application.

3.4.3 Discussion of State-of-the-Art Versus Requirements

The requirements of this investigation were to locate instruments capable of cryogenic pressure measurements within an accuracy of two percent full range from temperature sensitivity error. In addition, the transducer should have long-term operational capability in a space environment and should be reliable after many reuses. Light weight, small package size, simplified wiring requirements, low electrical power and simplified maintenance procedures are other desirable characteristics for future space vehicles. Measurement redundancy and redundancy management provisions are necessary considerations for future space missions.

This investigation has found that currently available equipment cannot meet all of these requirements. It is clear from the investigation that no single transducer design is capable of making measurements to an accuracy of two

percent full range under all of the conditions encountered in cryogenic usage. Furthermore, no designs either in the concept or in the development stages, except as noted in Paragraph 3.7 herein, were identified which have the potential of meeting the two percent goal.

Performance capability of the transducers in this survey are evaluated primarily upon cryogenic temperature capability, since this is the single performance capability which current technology cannot satisfy for potential future needs. Of the total number of units indicating cryogenic temperature capability, only four manufacturers' parts are rated as operable in the liquid hydrogen range. These units are:

MB Electronics, Series 172	Strain Gage, Bonded
Bell & Howell Type 4-361 and 4-356	Strain Gage, Unbonded
Kistler Models 601 and 603A, 603H	Crystal
Genisco Models 103, 419, 513, 519 and 923	Strain Gage, Bonded

All other remaining units are rated to -320 F with the Kistler Model 606 rated to -350 F. Not all the instruments listed as operable in the cryogenic temperature range are temperature compensated over the full range. This may be due more to a convenience factor than to a capability factor. Since cryogenic transducers must be considered specialty items and instruments are usually purchased to customer specifications even though the instruments are basically considered off-the-shelf. Manufacturers indicate that temperature compensation can be provided for almost any operating temperature over the operable range. For comparison purposes, a tabulation is made for three typical instruments which are temperature compensated. The values are based on the assumption that instruments are calibrated at 77 F and operated at -300 F. Also, that the transducer temperature is uniform and stabilized at the temperatures indicated.

<u>Manufacturer</u>	<u>Error (% FSO)</u>
MB Electronics	5.6
Statham	7.5
Kistler	3.8

The values point out that under the conditions specified, the errors exceed the value established as a design goal for this investigation. In the case where the transducer is calibrated at -300 F and operated at this temperature under uniform and steady-state conditions, it is expected that the temperature error would be reduced to a value approximating room temperature values. Unfortunately, in real applications, this ideal condition of a steady-state and uniform temperature environment is a rare condition. One of the few applications where this environment may exist is an installation where the transducer is located internally in a propellant tank. Under tanked conditions the transducer operates at the cryogen temperature.

The largest number of cryogenic pressure measurements involves installing the transducer external to the tank or feedline such that the transducer is exposed to the ambient temperature environments. For these applications,

temperature gradients from the sensing end to the connector end exist as a function of many variables. Primarily the ambient temperature, the transducer size and mass, and the insulation provisions are important influencing factors. For purposes of this immediate discussion, it is enough to know that thermal gradients exist and that these gradients contribute to temperature induced errors. The following discussions provide the details on the significance of these gradients.

3.4.3.1 Temperature Gradient Effects

In a paper by Mr. Leon Horn [16], the conclusion was made based on test results that thermal gradients can cause variations in the zero shift up to 100 percent FSO with transducers that indicated less than six percent shift in standard steady state temperature tests. Mr. Horn, working with transducers whose typical zero shift was between 0.01 percent to 0.02 percent FSO/F for uniform temperature conditions, found that when instruments were tested, such that one surface of the transducer was exposed to a hot medium and the opposite end to a cooler environment, the temperature compensation was itself the cause of a zero shift large enough to invalidate any tests being performed, since the temperature-compensating network was not at the same temperature as the active elements of the device. He concluded that the total zero shift can be considered to be made up of two parts; one, the normal shift due to the temperature on the face of the transducer and the other due to the gradient which was found to account for almost five times the error in at least one test transducer.

The test was conducted by Mr. Horn using an electric soldering iron as a heat source, and the heat was transferred to the transducer by thermal contact to an installation plate. A maximum front surface temperature of 600 F was used with a heat output of 3 cal/cm².

The test was designed on the basis that a temperature gradient was developed within the pressure transducer that is similar to the gradient expected under field conditions. Also, the test was designed to measure the time-temperature constant of the test specimen transducers. Excerpts from Mr. Horn's test report are provided below.

Figure 3.4.3.1-1 shows the results of temperature tests to determine the zero shift in the calibration of one particular temperature-compensated pressure transducer. The instrument was advertised as having an allowable zero shift of 0.02% FSO/F from -45 to 600 F. The instrument was found to operate within the indicated limit for uniform steady-state temperatures. One finding of the program was the fact that the transducer response to gradients was not predictable from specification performance values.

Figure 3.4.3.1-2 shows the zero shift of the same transducer as a function of time and temperature and thermal gradients as listed below:

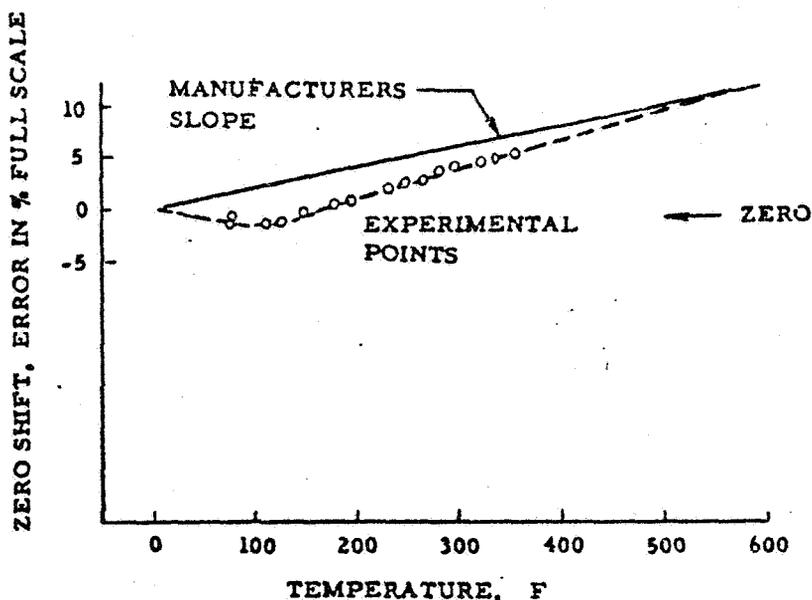


Figure 3.4.3.1-1. [16] Pressure Gage Zero Shift (Gradients)

Curve No.	Transducer Code	Max Temp on Face (F)	Conditions of Test Back Surface
1	A-3	300	Cool air on back
2	A-3	375	Exposed, no cooled
3	A-3	380	Cool air on back
4	A-3	530	Exposed, not cooled
5	A-3	545	Cool air on back

The difference between Curves 2 and 4 is the result of increasing the initial temperature and the flux rate of the heater. The transducers were allowed to approach the temperature of the heater as rapidly as their design would permit. Curves 1, 3, and 5 differ in the fact that cooling air was blown across the back surface of the gage, thus causing a larger gradient to be established.

A comparison between air-cooled and normal gage installation at one input, Curves 1 and 2, and those at a higher input rate and temperature, Curves 4 and 5, indicated that: (a) the zero shift for a gradient is far more than that

indicated by the uniform steady-state temperature tests; (b) cooling the back increases the eventual zero shift, although for the same input, it requires a longer time for the maximum to be reached.

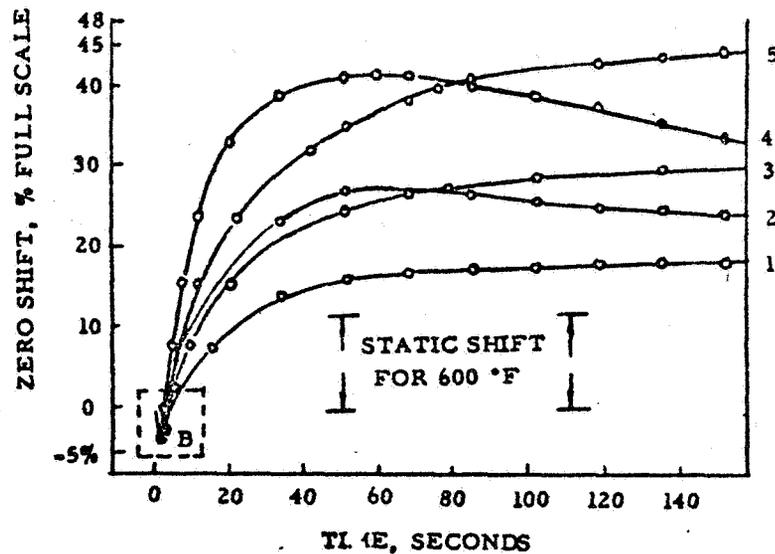


Figure 3.4.3.1-2. [16] Pressure Gage Zero Calibration (Static)

The rate of zero shift is related to the heat flux input and the amount of zero shift is related to the gradient established.

A study of the results of a number of tests with different transducers indicated that the time to produce the maximum gradient for a normally installed pressure transducer was a constant of the design and material and was not altered by the heat flux rate for the temperature range studied and the materials encountered.

Figure 3.4.3.1-3 is an enlargement of the initial response of the particular smooth diaphragm pressure transducer enclosed in the dotted region in Figure 3.4.3.1-2. The trace is shown as dotted for the first second, since the resolution of the output is not sufficient to determine the precise value of the zero level within this period of time. The negative shift followed by a recovery was apparent in every run, although the time to reach a minimum was not certain. The effect was similar to what is known as "oil-canning" and was followed by a relatively rapid recovery. For a period of almost five seconds, no valid data were obtained. The heat flux input seemed to alter the response in a repeatable manner; curves 4 and 5 and 2 and 3 are the results of similar heat flux input.

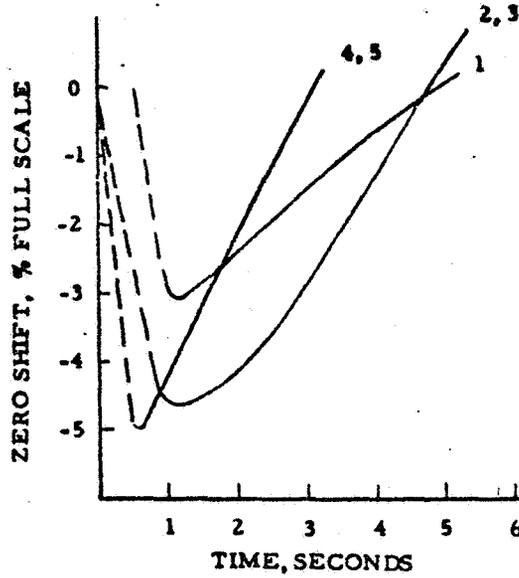


Figure 3.4.3.1-3. [16] Enlargement of Area B

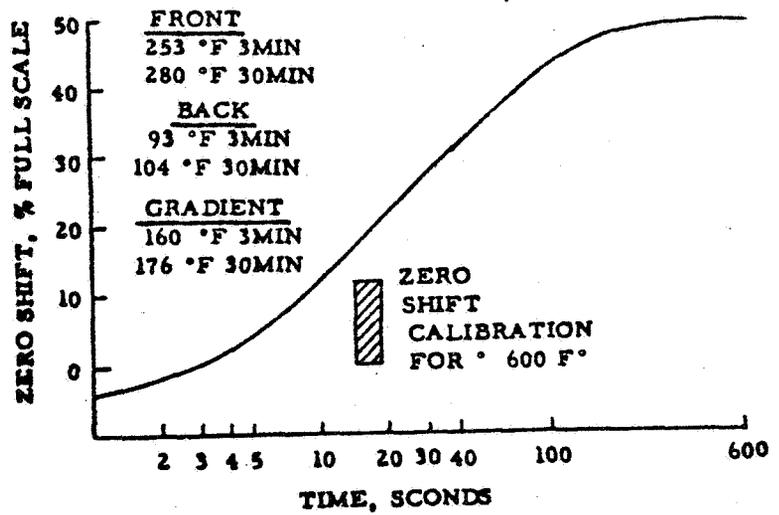


Figure 3.4.3.1-4. [16] Long Term Gradients

Figure 3.4.3.1-4 shows the results of maintaining a heat source on the active surface of the transducer while a stream of cooling air was maintained across the back of the same transducer. At the end of ten minutes the transducer was approaching a steady-state condition with a zero shift of almost 47% of full scale. At the end of 30 minutes the zero shift had stabilized at 48% of full scale and appeared to have reached a condition of equilibrium. The conditions for this test were the same as for Curve 5, Figure 3.4.3.1-2.

Figure 3.4.3.1-5 is a typical output of one transducer; but in addition to the zero shift, the temperature values of both ends of the transducer are shown. For the particular unit tested, the back surface showed a change in its rate of temperature increase at about 51 seconds. This time was the same as long as one did not alter the general configuration of the test equipment.

Changes in the rate of heat flux or the temperature of the heater did not change the time for this event within the range available (0.8 cal/cm² to 8 cal/cm²). Within measurement accuracy, all that increasing the energy input did was to increase the slope of the zero shift curve and to increase the gradient maximum. On this graph an arrow mark indicates the time of the zero shift maximum. Transducer A3 was used for this test with the front face exposed to 250 F and the back exposed but not cooled.

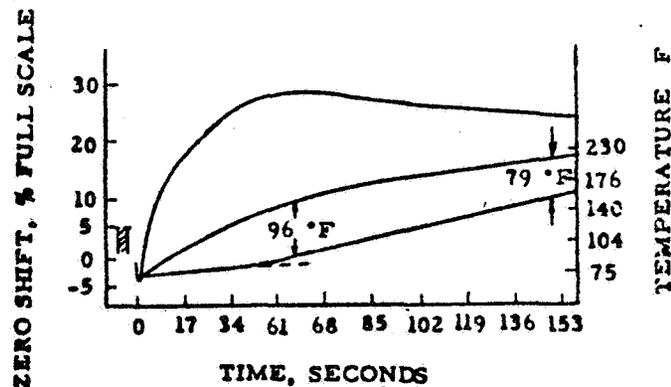


Figure 3.4.3.1-5. [16] Temperature Gradient Effect on Zero Shift

Figure 3.4.3.1-6 represents the data obtained from tests of three different transducers. A and B are unbonded strain gage pressure transducers by two different manufacturers. Both checked out as anticipated based on manufacturer's data for the uniform temperature test, but B continued to hold well within the same limits when exposed to thermal gradients, while A

responded with a large zero shift. Curve C represents the response of a differential transformer pressure transducer.

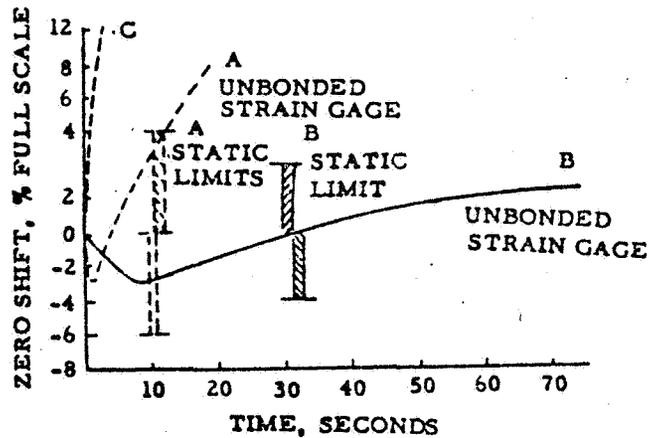


Figure 3.4.3.1-6. [16] Thermal Response

Conditions of the Figure 3.4.3.1-6 test are as listed below:

Curve	Transducer	Max Temp. on Face (F)	Conditions of Test Back Surface
A	A-3	250	Exposed, not cooled
B	B-11	300	Exposed, not cooled
C	B-12	212	Exposed, not cooled

Figure 3.4.3.1-7 illustrates some of the wide variations found in the reactions of flat diaphragm pressure transducers to thermal gradients. The unit shown on Curve B indicated normal operation in the standard furnace temperature tests both before and after a thermal gradient test was applied, but it became inoperative during a gradient test in less than 20 seconds. When exposed to a thermal gradient of more than 80 F, there was more than a 100% FS zero shift.

The lower dotted curve is another pressure range of the same series from the same manufacturer with still another kind of response to a gradient. This gage did recover and after 40 seconds was within the zero shift limits for successful uniform temperature compensation.

Conditions of the Figure 3.4.3.1-7 tests are listed below:

Curve	Transducer	Max. Temp. on Face (F)	Conditions of Test Back Surface
A	B-13	200	Exposed, not cooled
B	B-8	230	Exposed, not cooled

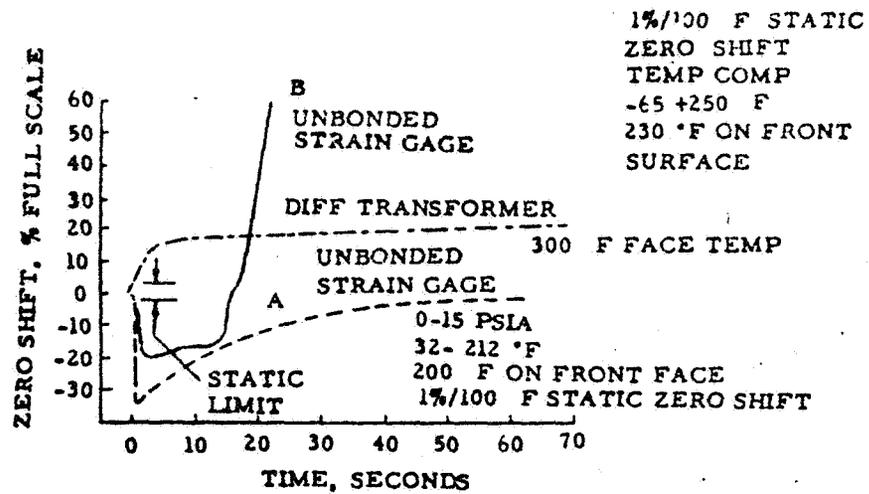


Figure 3.4.3.1-7. [16] Thermal Response

Based on the test results, the conclusions reached by Mr. Horn are:

- Flush-mounted pressure gages may check as fully temperature-compensated during standard temperature tests and still show zero shifts of up to 100% FS for thermal gradients within the operating temperature range of the transducer.
- The reaction to thermal gradients for presumably similar pressure gages made by different manufacturers is so diverse that it masks differences that may exist due to types.
- Each transducer tested had a "time to maximum" zero shift. This "time" was a constant for a particular transducer design and material. It was not altered by changing the flux rate.
- Although the rate of energy input and thermal flux density influence the magnitude and the time it takes to reach a given gradient value, it is the temperature gradient that is responsible for the zero shift of the instrument.

- e. For a steady-state gradient there is a fixed zero shift.
- f. Cooling the back surface of the transducer increases the thermal gradient and thus the zero shift.

"Oil Canning," when it occurs, causes a self-reversing zero shift during the first few seconds after the application of a change in the surface temperature.

The tests conducted by Mr. Horn were all performed at elevated temperatures; however, the gradients established are expected to have similar results on transducers at the low temperature environments. The significant points established by Mr. Horn are that pressure transducer specification values under uniform temperature conditions provide no assurance that the instruments will perform within these specification limits under transient temperature conditions. Further, he points out that transducers which normally operate with a temperature error of approximately six percent FSO over a given temperature span may exhibit errors many times this value in field applications where temperature gradients exist.

3.4.3.2 Simulated Field Condition Tests

In another test program conducted by Messrs. Kinzie and Murphy,^[15] cryogenic pressure transducers were tested under simulated field conditions. The program involved laboratory evaluations of commercial cryogenic pressure transducers for performance capability during sudden exposure to liquid nitrogen and liquid hydrogen temperatures. The purpose of the work was to evaluate the performance of transducers during exposure to cryogenic temperature transients and to develop methods for improving the performance of promising models.

The test environment simulated by the authors includes two types of field conditions. The first called Overall Ambient Environment (OAE) test simulated a condition where the transducer was exposed suddenly from a room ambient temperature condition to a turbulent external atmosphere at a temperature near the boiling point of liquid nitrogen. This environment was created by plunging a cylinder with a transducer installed into the interior of an environmental chamber which had been initially stabilized near the boiling point of liquid nitrogen. The transducer could be made to sense a known reference pressure in this arrangement.

The second test, known as the Pressurant Fluid (PF) test was designed to simulate an application where the transducer, installed in the wall of a large pipe or chamber and initially at room temperature, is exposed to a flowing cryogenic liquid. This condition was created by suddenly introducing a cryogenic liquid at the pressure port or diaphragm of the transducer. The test setup to simulate this condition was accomplished by installing the test transducer to the under side of a Dewar with the stream directed at the transducer. This arrangement could also be modified to test above atmospheric pressure.



Under the conditions of the Overall Ambient Test (OAE), 26 transducers were tested, which were supplied by eight manufacturers and represented 12 model types. The authors found a wide variation in transducer responses even between identical models. Three readily distinguishable signal responses have been identified as characteristic outputs for the instruments in general with one case where all three responses were evident in a single instrument. The observed apparent pressure outputs after exposure to the cryogenic environment are:

A pronounced peak of apparent pressure occurring after a few seconds from the exposure and continuing for several minutes.

A second characteristic transient response consisted of a peak apparent pressure which took many minutes to develop. A number of transducers displayed both the fast and the slow transient peaks.

A third characteristic occasionally occurred which consisted of a long period of drift which continued throughout the test for the 20 to 45 minutes.

Pressurant Fluid tests were conducted on a total of 20 transducers of ten different model types. In general, it was found that the larger, more massive units with restrictions to the inlet tube leading to the transducer cavity performed better during the PF tests than during the OAE tests. The flush diaphragm units did not perform well during the PF tests, but performed better during the OAE tests. Flush diaphragm transducers and a few of the less protected cavity units exhibited apparent fluctuations of several cycles per second.

For Pressurant Fluid tests above atmospheric pressures, it was necessary to reduce the number of units tested; therefore, an effort was made to choose transducers most likely to perform well at higher pressures. A total of nine transducers were selected from four manufacturers. The PF tests for these instruments were conducted over a period from one to five minutes only.

In every case, the magnitudes of the maximum apparent pressure are higher than the corresponding values for the atmospheric pressure test. It was speculated that even greater increases in apparent pressure would have been observed during test of the more massive units had it been possible to extend the test period to some 15 or 20 minutes duration as was done at atmospheric pressure. The apparent pressure fluctuations observed during the atmospheric PF test were more pronounced during the above atmospheric tests.

Messrs. Kinzie's and Murphy's interpretations of the test results are provided below. In most cases, the words are presented verbatim to preserve the accuracy of their conclusions.

The authors found three important factors contributing to the transducer transient performance. They point out that the interrelation of each of the three factors with each other could not always be determined and that in some cases the possibility existed that the transducer was responding to all three factors simultaneously. The factors identified are: (1) compensating resistor isolation, (2) diaphragm distortion, and (3) apparent pressure fluctuations.



In the first case, the authors indicate that all of the transducers which were evaluated had at least some of the bridge signal conditioning resistors mounted in a manner which thermally separated them from the active strain gages; and in some cases, the resistors were also isolated thermally, by differing degrees, from the diaphragm and from each other. Upon sudden case exposure to a cryogenic atmosphere, as in an OAE test, these resistors cool much more rapidly than the active gages. When active compensators are affected in this way, the accompanying resistance changes lead to zero shift and sensitivity changes in the transducer characteristics, and give rise to the fast transient peak mentioned earlier. The fact that the degree of isolation of each compensator can vary may explain some of the complex signal variations which were observed near the start of a number of tests. After a period of exposure time, the active gages also cool to some degree. Depending upon the thermal characteristics of the transducer-simulated structure system, an intermediate condition is reached where a slowly decreasing temperature gradient exists from the partly cooled stainless steel cylinder (installation fixture), through the still colder transducer, to the cryogenic atmosphere. The transducer is still relatively warm due to the boundary layer temperature drop between the case and the atmosphere. Only partial temperature compensation can occur during this period, depending upon the magnitude of the internal temperature gradient. It is possible that in some cases, the slow transient condition is associated with this gradient, depending upon the location and manner in which the compensators affect the transducer output.

Finally, after many minutes, the entire system approaches the temperature of the surrounding atmosphere. The internal temperature distribution of the transducer changes at an every decreasing rate, the internal temperature gradient becomes small, and the steady state temperature compensation error tends to predominate, provided that the surrounding atmosphere remains at a constant temperature.

In the case of diaphragm distortion effects, the authors found that the sudden exposure of a transducer to liquid nitrogen during a PF test produced something more than a simple reversal of the temperature distribution seen during an OAE test. The authors point out that the isolating of compensating resistors from the active gages is not the sole error source. They point out that if compensator isolation were the sole error source, a reversal of the polarity of the peak apparent pressure signal would be seen when the compensators were warmer than the active gages, rather than vice versa. With some possible exceptions due to unusual construction, the compensators were colder than the active gages during the OAE tests, and warmer during the PF tests. As seen from the tables, there are only three transducer models which show a consistent polarity reversal in comparing the two tests.

A major contributor to the observed PF test results, at least where polarity reversal did not occur, is believed to be the error caused by diaphragm behavior during thermal gradient conditions in the diaphragm and its supporting structure. In such a situation, the diaphragm cools much faster than its supporting structure, giving rise to thermal stresses. A somewhat similar but less pronounced condition can occur when the transducer case is cooled, which imposes thermal stresses on the diaphragm through the supporting structure. The authors conclude that the deflection pattern of the diaphragm, and consequently the zero balance and possibly the sensitivity of the strain gage bridge circuit, are affected by these conditions.



The apparent pressure fluctuation conditions observed by Kinzie and Murphy are believed to be associated with temperature shock effects at the pressure diaphragm. This condition is distinguished from the diaphragm distortion effects as described previously by the fact that it is thought to be associated with localized effects of cryogen turbulence over portions of the diaphragm surface rather than the relatively slowly changing gradient conditions associated with thermal distortion of the entire diaphragm and supporting structure. The authors point out that it is surprising that this same fluctuating condition does not exhibit itself during conventional immersion tests where the transducer is plunged into a Dewar of cryogen diaphragm-end-first.

The zero shift error found from the simple immersion test for one transducer is less than five percent FSO. In contrast, the PF test results indicated apparent pressure values of -129 to 15.2 percent FSO for the same unit and -5.51 percent FSO for another instrument which indicated only a one to two percent figure when immersed.

It is evident that the response of flush diaphragm transducers depends upon the manner in which liquid nitrogen is directed toward the diaphragm. When an immersion test is conducted, the diaphragm surface is above the boundary layer, which is at first produced by a stable film boiling condition. After sufficient cooling, however, transition to nucleate boiling occurs. Finally, boiling ceases as the entire transducer reaches liquid nitrogen temperature. In contrast during the PF test at atmospheric pressure, a stream of liquid nitrogen falls upon the diaphragm, at first giving rise to an intermittent and non-uniform film boiling condition as the mixture of liquid and vapor impinges upon the diaphragm surface. Even when a relatively deep layer is established above the diaphragm, there must still be considerable turbulence compared with the immersion condition. In any case, it is likely that a very non-uniform and continually changing temperature distribution exists in the diaphragm, resulting in both thermal stresses and unequal temperature environments for strain gages.

A summary of the findings are provided below:

The authors found that large massive transducers with inlet ports which had a diffuser protected cavity generally operated satisfactorily for at least the first few minutes after the initial transient temperature change.

Flush diaphragm transducers tested were all found to be unsuitable for pressure measurements under the simulated transient condition of flowing cryogenic fluids. The instruments tested were found to exhibit ten to fifty percent FSO or more error for periods of many minutes after sudden exposure to the cryogenic flow.

It was found that the performance of a transducer could not be predicted under sudden cryogenic flow conditions based on a performance under a sudden immersion or dip test, which is commonly performed as a test environment or during the calibration procedure. This finding was most

applicable to flush diaphragm units which are normally tested by plunging the transducer into the cryogen diaphragm first; but, it also was true for some cavity-type transducers.

Several conclusions were drawn by the authors from the findings.

The performance of existing transducers could be improved by modification of the instruments with larger heat sink provisions. This improvement satisfies transients of a few minutes duration.

In the case of new transducer designs, the authors felt that the most important improvement could be made by placing the bridge temperature compensation resistor in the same thermal environment as the strain gage elements. The authors have found that under current practices in the industry, all or most of these components are installed on a separate plate or terminal board.

Existing flush diaphragm transducers can be adapted for cryogenic usage by the installation of a protective cap and inlet port diffuser assembly.

New flush diaphragm transducer designs should incorporate provisions to minimize errors associated with flow conditions. These design changes should be made to decrease diaphragm distortion effects and to decrease bridge sensitivity to diaphragm radial temperature gradients.

As a recommendation, the authors indicate that the use of heat sink protected cavity-type transducers be used for liquid hydrogen transient flow conditions. For applications requiring small transducer sizes, low heat capacity and high frequency response and good temperature compensation, Kinzie and Murphy recommended that a new transducer be developed.

3.4.3.3 Low Temperature Performance Evaluations

Messrs. Dean and Flynn^[18] of the National Bureau of Standards evaluated selected pressure transducers which were specifically advertised as cryogenic pressure transducers. They found that all of the transducers tested had various degrees of sensitivity and zero shifts as well as temperature-gradient effects sufficiently large that the instruments would fail to meet specification limits being written by the Space Technology Industry at the time. Figure 3.4.3.3-1 is presented to show the performance results of a well-known cryogenic strain gage pressure transducer. The authors indicate that this transducer could not be installed directly on the fuel manifold of a liquid-hydrogen rocket engine if meaningful pressure information during cooldown and startup was desired.

Based on the knowledge that a problem existed in cryogenic pressure instrumentation field, the authors conducted an investigation with the objective of obtaining a better appreciation of the instrument designers' problems and also to develop some useful suggestions on the proper installation and application of transducers for cryogenic pressure measurements.

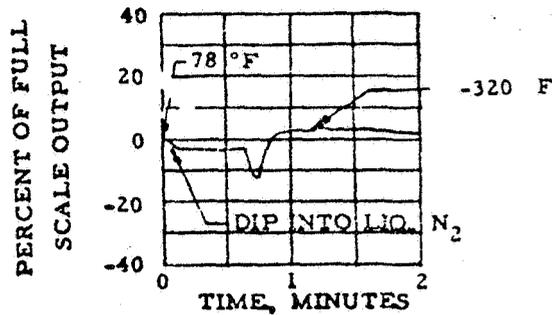


Figure 3.4.3.3-1 [18] Results of a Thermal-Shock Test of an Unbonded Strain-Gage Pressure Transducer Designed for Cryogenic Service

Engineering analysis conducted by the authors for a typical pressure transducer configuration reveals from equations developed that the expansivity and Young's modulus temperature coefficients may be calculated from the slopes of the plots in Figures 3.4.3.3-2 and 3.4.3.3-3. They calculate that for transducer constructed from 410 stainless steel throughout the expansivity value is approximately 0.001%/F and the Young's modulus coefficient for the deflection members is 0.01%/F. Thus, the more significant Young's modulus factor contributes to a sensitivity shift of approximately -3% at liquid nitrogen temperatures and +3% at +300 F.

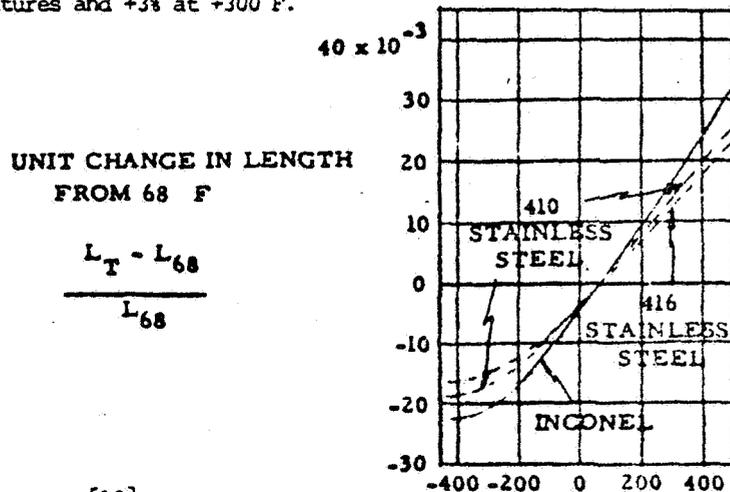


Figure 3.4.3.3-2. [18] Calibration of a Bonded Strain-Gage Pressure Transducer at Several Temperature Showing Zero Shifts

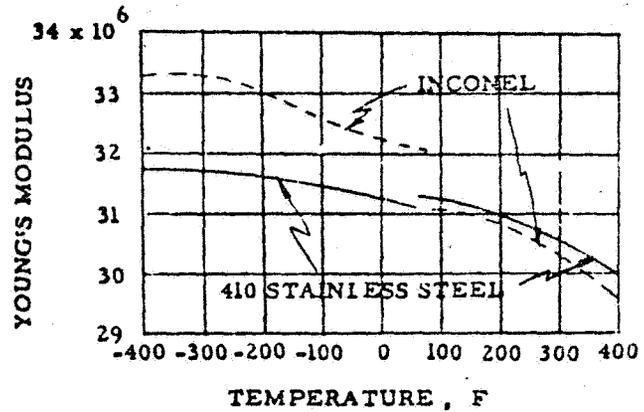


Figure 3.4.3.3-3. [18] Young's Modulus of Several Metals

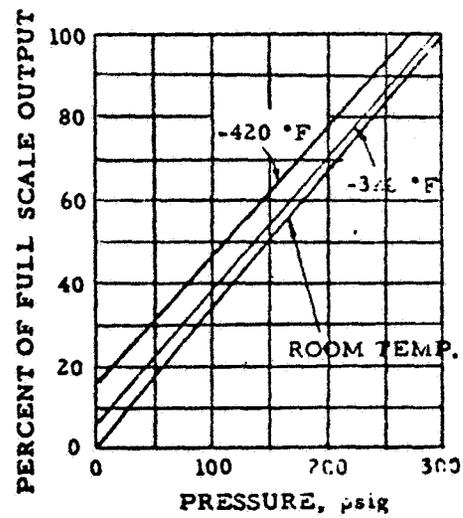


Figure 3.4.3.3-4. [18] Calibration of a Bonded Strain-Gage Pressure Transducer at Several Temperatures Showing Zero Shifts

Zero shift, which is the parallel displacement of the calibration curve, is described by the authors with an equation which establishes the zero shift as a function of expansivities and length of the components. An example for zero shift is shown in Figure 3.4.3.3-4 for a bonded strain gage transducer. The authors point out that little can be done to reduce the temperature dependency of Young's modulus but proper design can reduce the effects of the expansivity of the components. Figure 3.4.3.3-5 is a record of the temperature shock of a potentiometric type pressure transducer designed to minimize expansivity effects. Zero shift on dipping the transducer into liquid nitrogen is less than 1% FSO. The peaks of the plot were caused by vibration used to keep the wiper from freezing to the potentiometer.

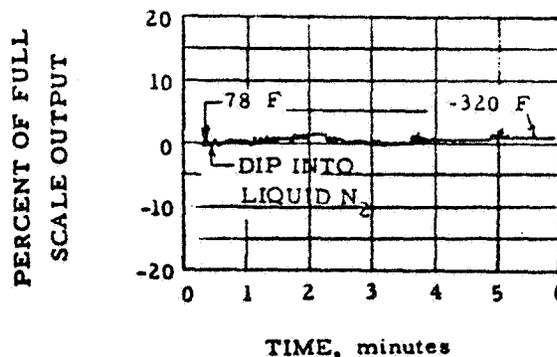


Figure 3.4.3.3-5^[18]. Zero Shift Caused by Thermal Shocking of a Helically Coiled Bourdon-Tube-Actuated Potentiometric Pressure Transducer

The authors indicate that, although the transducer performed well with respect to low zero shift, the instrument was sensitive to cross axis vibration and to Young's modulus temperature dependence. The investigator concluded that until a design can be found that can reduce temperature effects, the best solution is to avoid extreme temperature environments. The procedure is that when the pressure instrumentation point is at an extreme temperature, a sense line is used to a remotely located transducer. This procedure provides acceptable data for frequency responses to approximately 10 Hz. The authors point out that in an actual installation, the velocity of sound is a function of the pressure and temperature of the measurement and whether it is a gas or liquid. In the case where the state of the fluid is variable, rigorous calculations of the resonant frequency are not possible. Figure 3.4.3.3-6 shows resonant frequency values for air based on the length and various temperatures. The figure provides some indication of the usable frequency range for a transducer tube system. The usable frequency range is between one-tenth to one-third of the resonance frequency value, depending on the system damping.

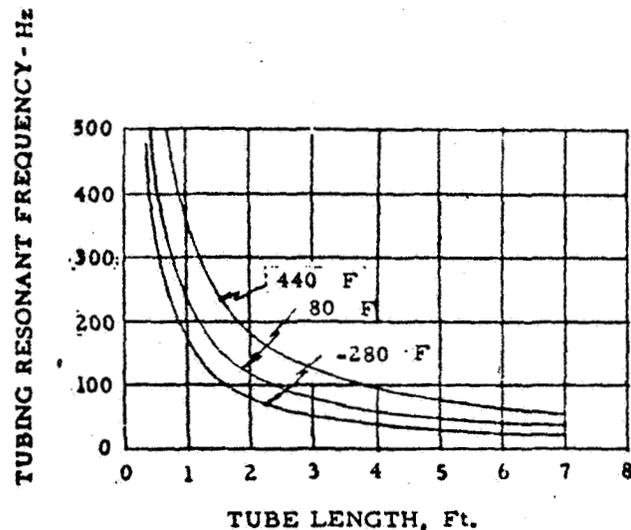


Figure 3.4.3.3-6. [18] Resonance Frequency of a Tube Calculated as for an Organ Pipe

3.4.3.4 Low Temperature Test Results

Smelzer^[17], in another National Bureau of Standards investigation, verified that a wide range of calibration variations take place between transducers from their initial room temperature calibration and re-calibration at liquid nitrogen and liquid hydrogen temperatures. The calibration variation ranged from 2.7 percent of initial full-scale output for the instrument with the smallest deviation to a maximum of 16 percent for the instrument with the greatest deviation. Transducer types tested include capacitance, potentiometric, unbonded strain gage and bonded strain gage units. The test data were the result of a program to establish the suitability of commercially available pressure transducers for operation at cryogenic temperatures, especially with liquid hydrogen. This investigation was initiated to overcome disadvantages of remotely installing the transducer from the sense point. Some of these disadvantages are: reduced frequency response, thermal oscillations, heat leak through sense lines, and potential fatigue failure of sense lines.

The procedure adopted for the test program consisted of calibrating the test instrument at ambient, liquid nitrogen and liquid hydrogen temperatures, thermal cycling the instruments between 70 F and liquid nitrogen temperature not less than fifty times at a constant pressure, and recalibrating at the three temperatures.



The conclusions resulting from the test program indicated that the unbonded strain gage units performed best of the units tested. It was concluded that accuracy results comparable to room temperature results could be achieved if the instrument was used over a narrow temperature span within the cryogenic range. In cases where large transient temperature excursions were imposed, the large transient errors made the use of any instrument questionable.

Of the four types of transducers tested the capacitance design was extremely temperature sensitive which is what the author expected. The bonded strain gage unit exhibited large calibration changes after thermal cycling and its zero pressure output after return to room temperature was erratic. One of two potentiometric units showed a marked hysteresis at low temperatures and the other unit performed with good results except for some non-linearity at low temperatures after thermal cycling.

Three unbonded strain gage units were tested with one of the three exhibiting the smallest error of any of the units tested. None of the three units tested showed any marked non-linearity, although the units showed large transient errors with thermal gradients. The unbonded units were the most stable during thermal cycling with the most stable unit exhibiting a change of approximately one percent of their initial room temperature full-scale output. Figures 3.4.3.4-1 through 3.4.3.4-12 show the test results described. The ratio E_0/E_i indicates output voltage (E_0) for two given input voltages (E_i).

3.4.3.5 Piezoelectric Pressure Transducer Evaluations

The investigation to this point leads to the identification of specific problems related to the accurate measurement of fluctuating pressures under transient cryogenic temperature environments. The previous investigations were primarily directed to strain gage pressure transducers utilizing compensating resistors. Piezoelectric pressure transducers do not normally utilize temperature compensation provisions other than in the selection of materials and in the physical design of case, diaphragm and other structural members. This design should not be as susceptible to the errors resulting from temperature gradients as was found in the previous evaluations.

In a Lewis Research Center investigation [19], temperature sensitivity tests were performed on piezoelectric pressure transducers from 20K to 477 K by Messrs. Lloyd W. Canfil and William C. Nieberding. The testing was performed with the setup shown in Figure 3.4.3.5-1. The test specimen transducers were installed on a manifold which was enclosed in a Dewar. Cryogenic tests were conducted by filling the Dewar with the appropriate cryogen, either liquid hydrogen or liquid nitrogen. A step pressure of approximately 100 psi was applied to the transducer and to a reference strain gage transducer. Signal outputs were recorded at a time after the pressure step where equilibrium was reached but before the charge amplifier output had decayed appreciably. Figure 3.4.3.5-2 provides the results of five transducers tested at various temperatures and compared with the room temperature calibration value. In addition, the results below were noted.

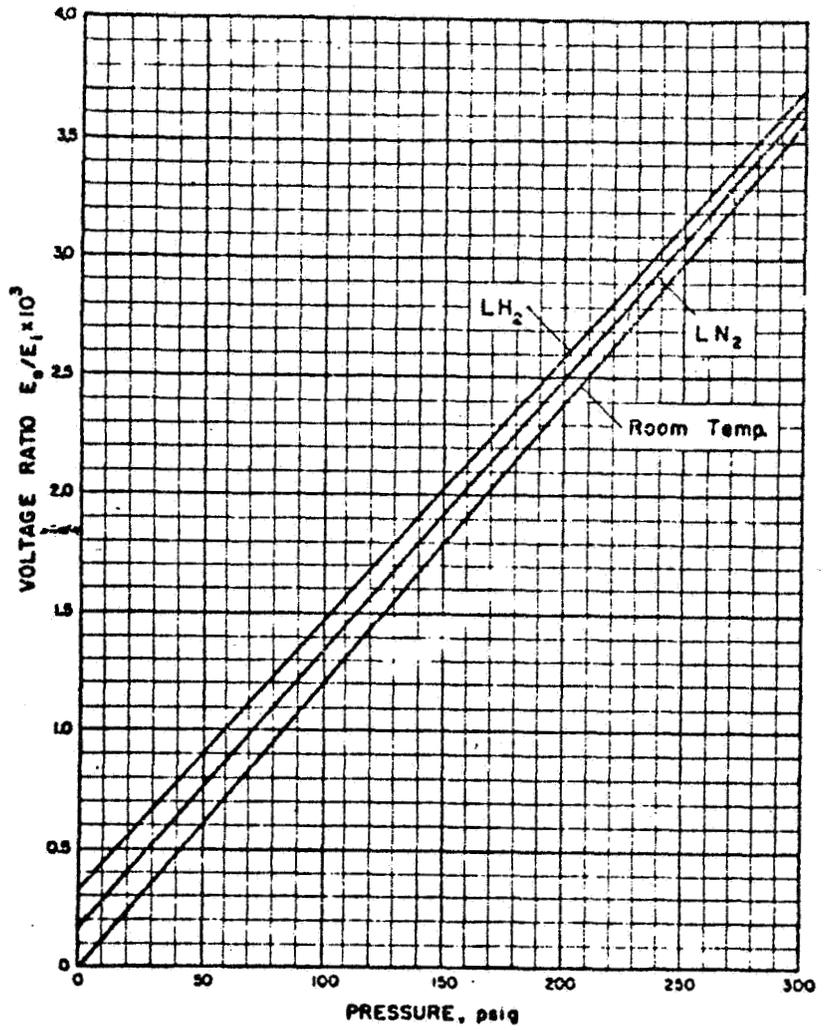


Figure 3.4.3.4-1 [17] Bonded Strain Gage. Pressure Range 0-300 PSIG

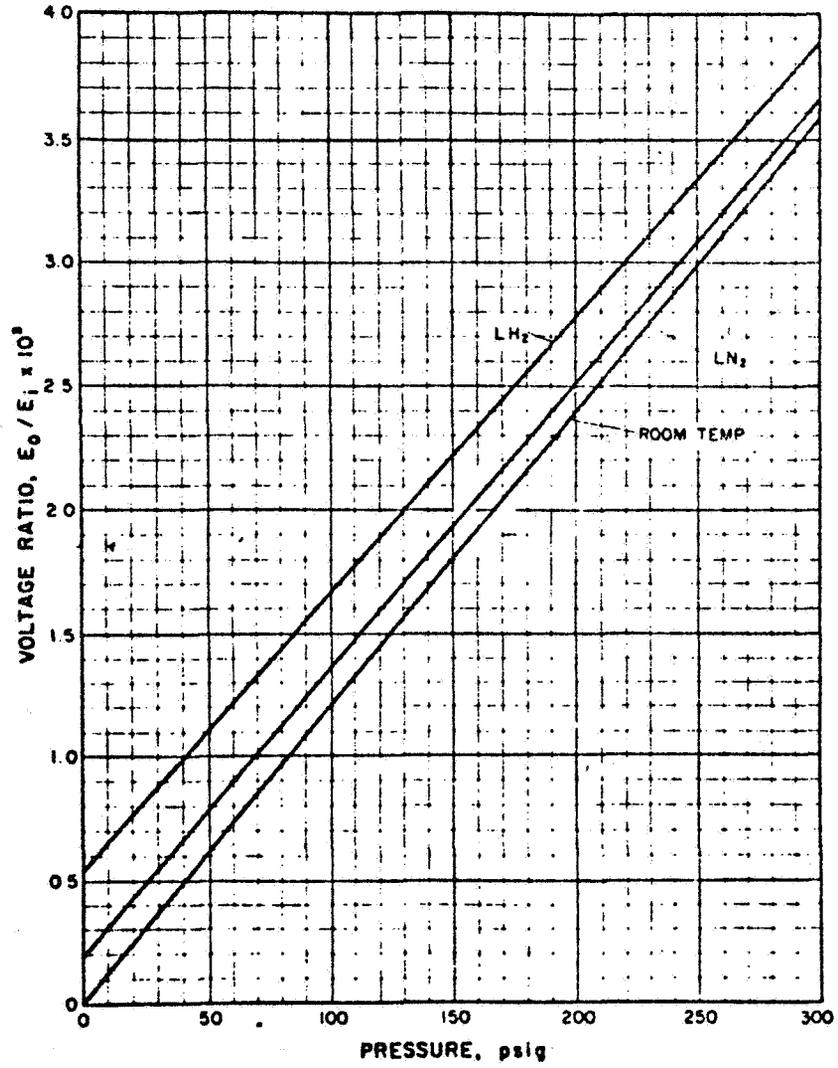


Figure 3.4.3.4-2 ⁰⁷ Bonded Strain Gage. Pressure Range 0-300 PSIG After Thermal Cycling

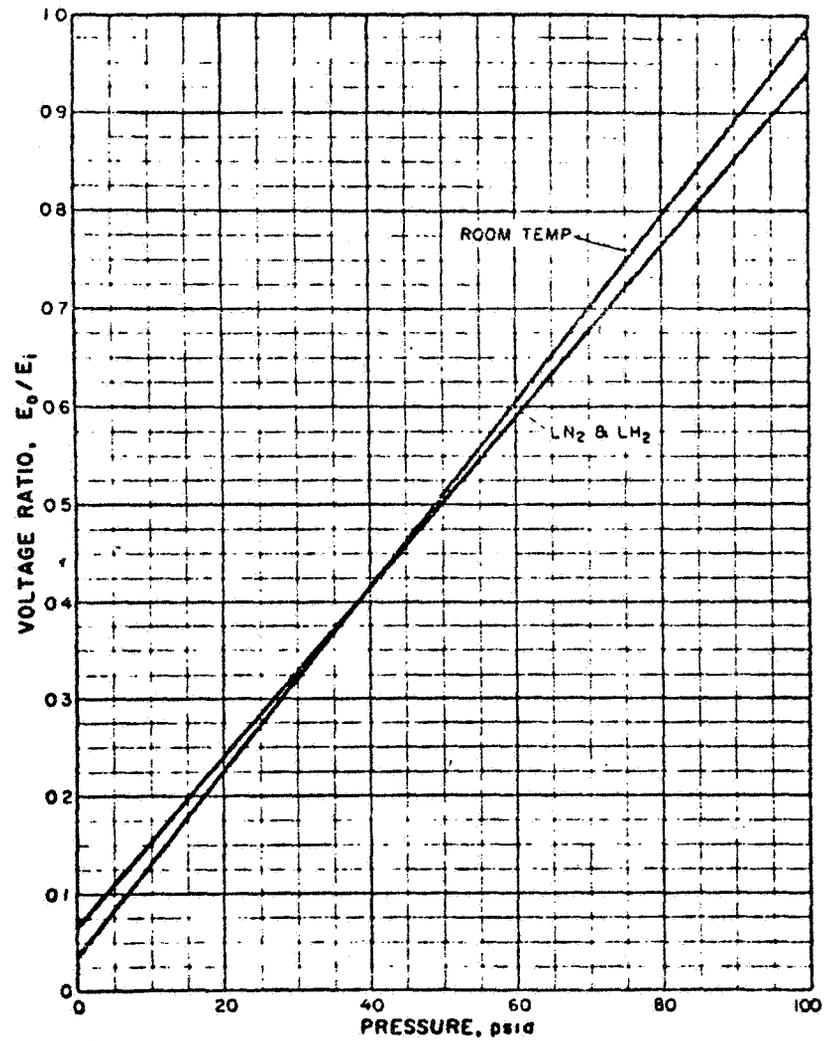


Figure 3.4.3.4-3 [1] Potentiometer Type A. Pressure Range 0-100 PSIA

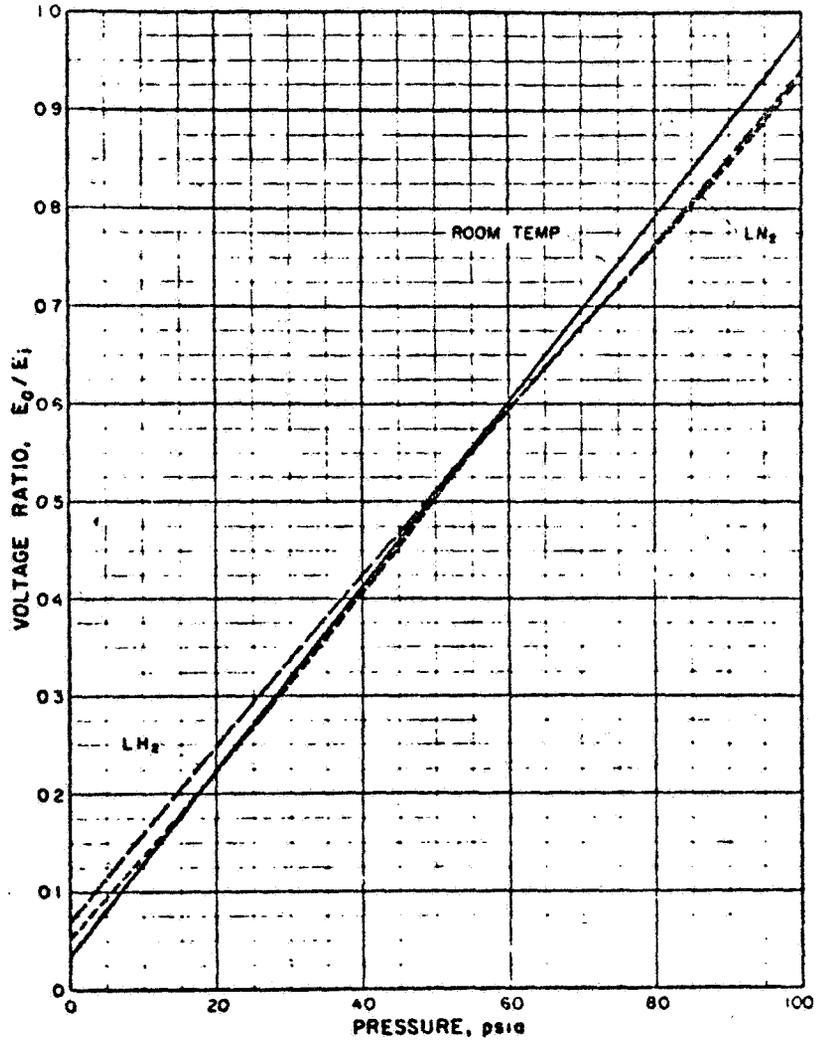


Figure 3.4.3.4-4  Potentiometer Type A. Pressure Range 0-100 PSIA After Thermal Cycling

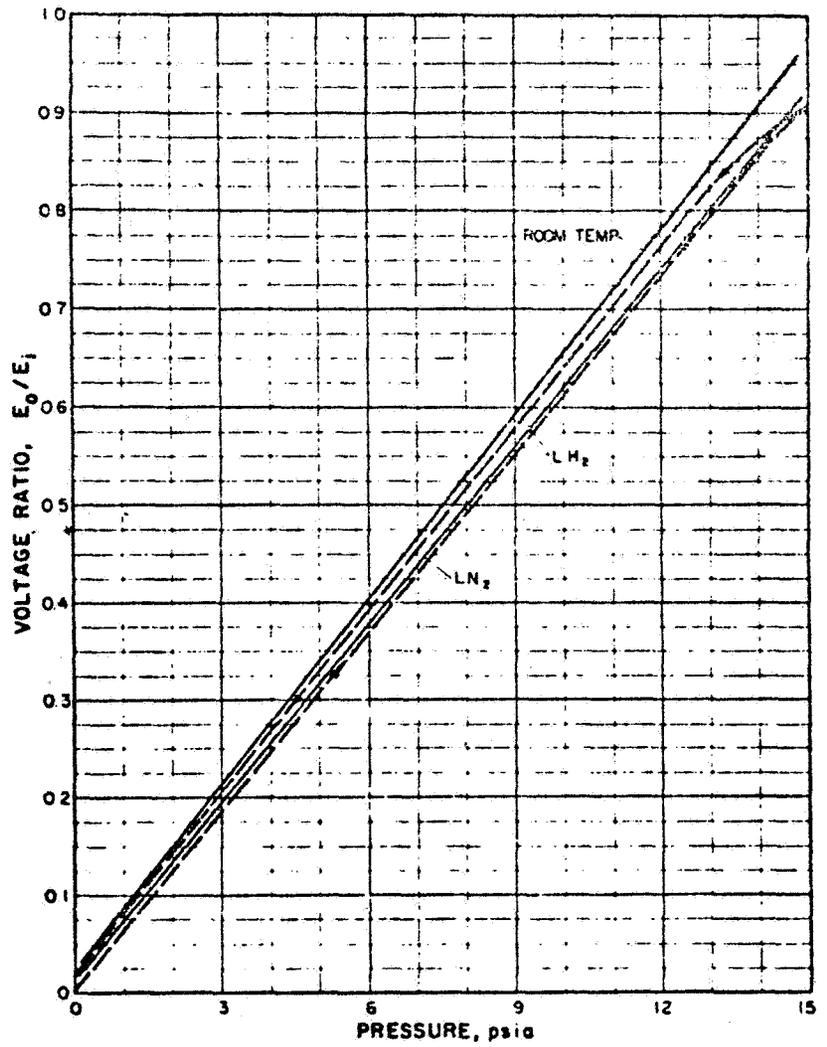


Figure 3.4.3.4-5 [7] Potentiometer Type B. Pressure Range 0-15 PSIA

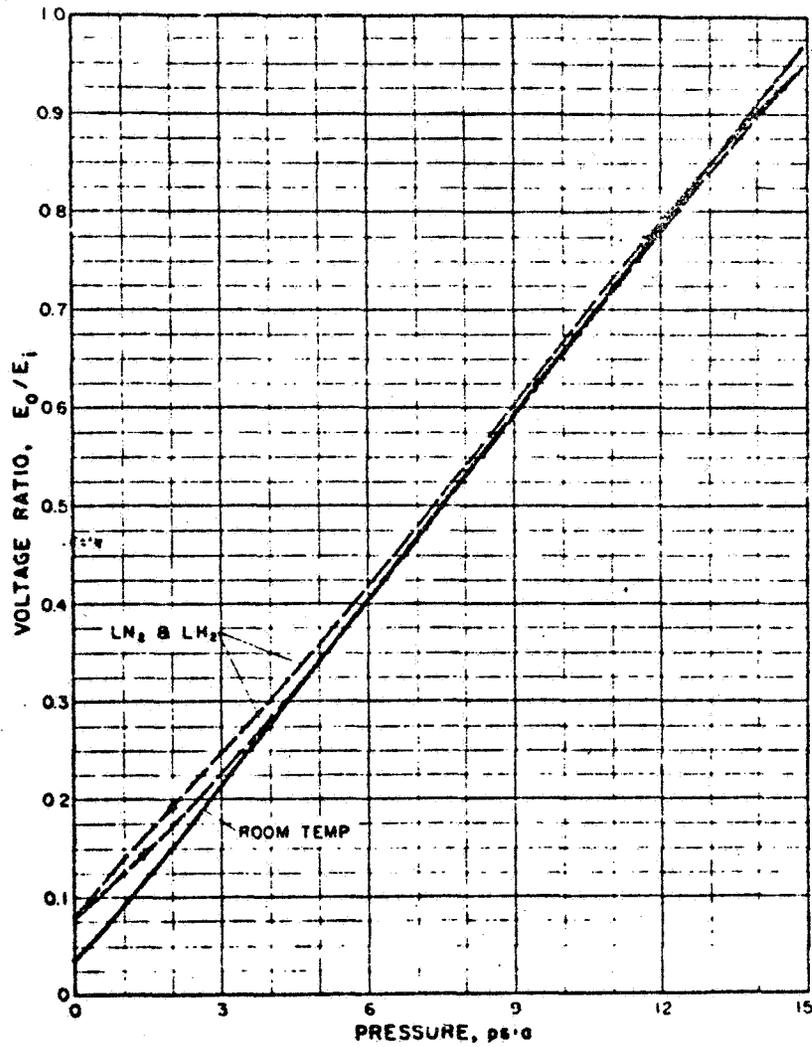


Figure 3.4.3.4-6 [17] Potentiometer Type B. Pressure Range 0-15 PSIA After Thermal Cycling

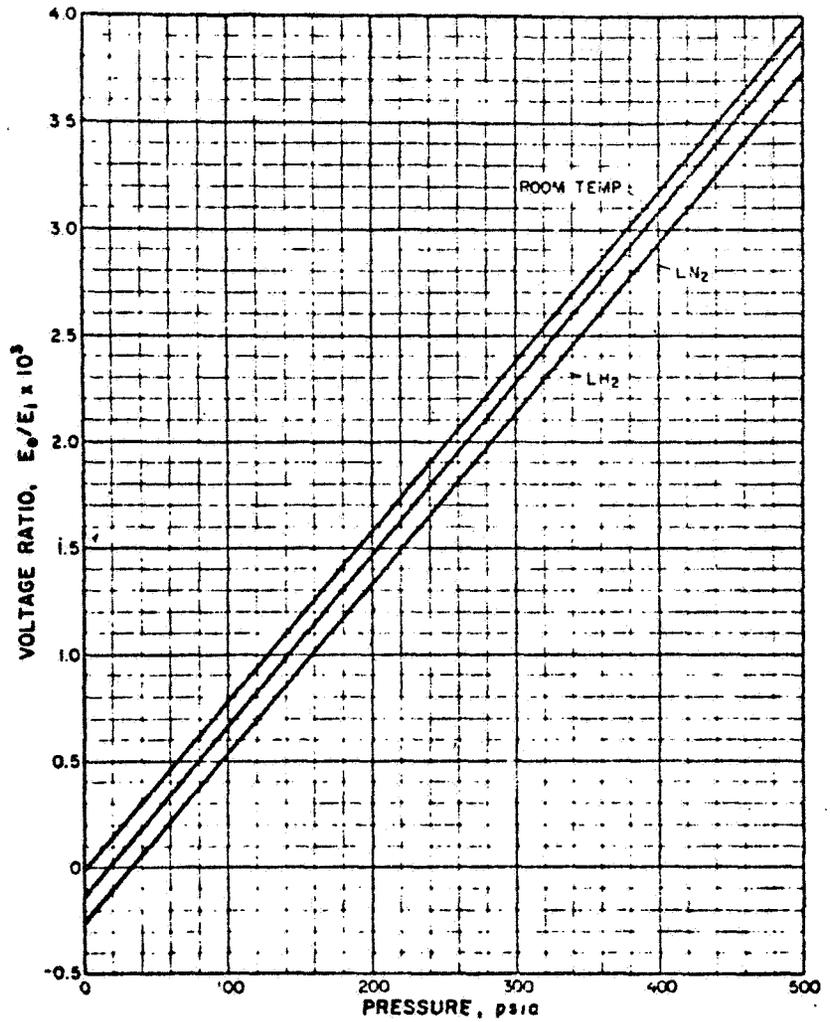


Figure 3.4.3.4-7 ¹⁷ Unbonded Strain Gage Type A. Pressure Range 0-500 PSIA After Thermal Cycling

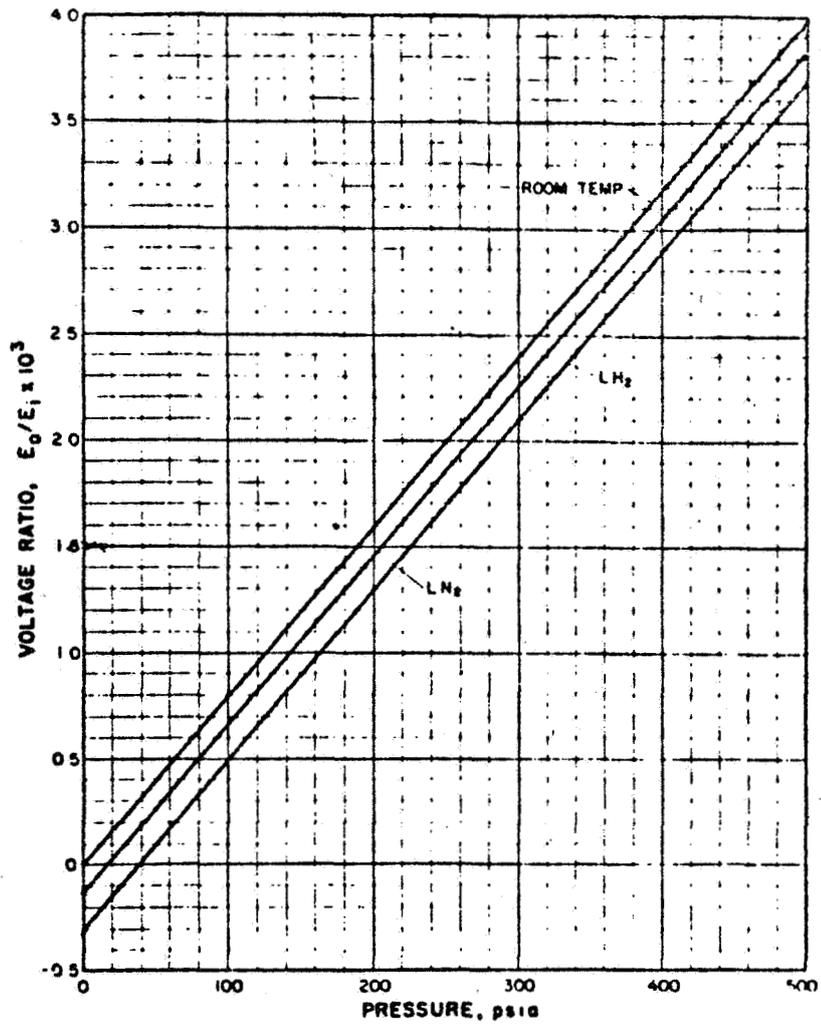


Figure 3.4.3.4-8 ¹⁷ Unbonded Strain Gage Type A. Pressure Range 0-500 PSIA

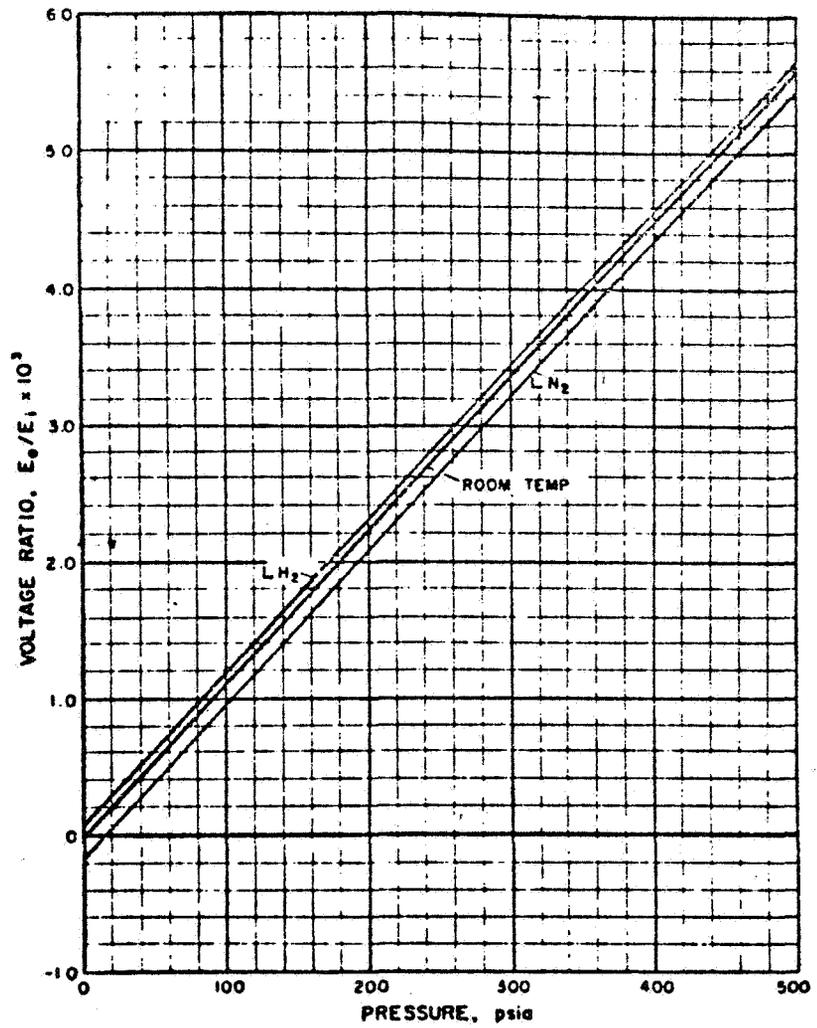


Figure 3.4.3.4-9 ² Unbonded Strain Gage Type B. Pressure Range 0-500 PSIA

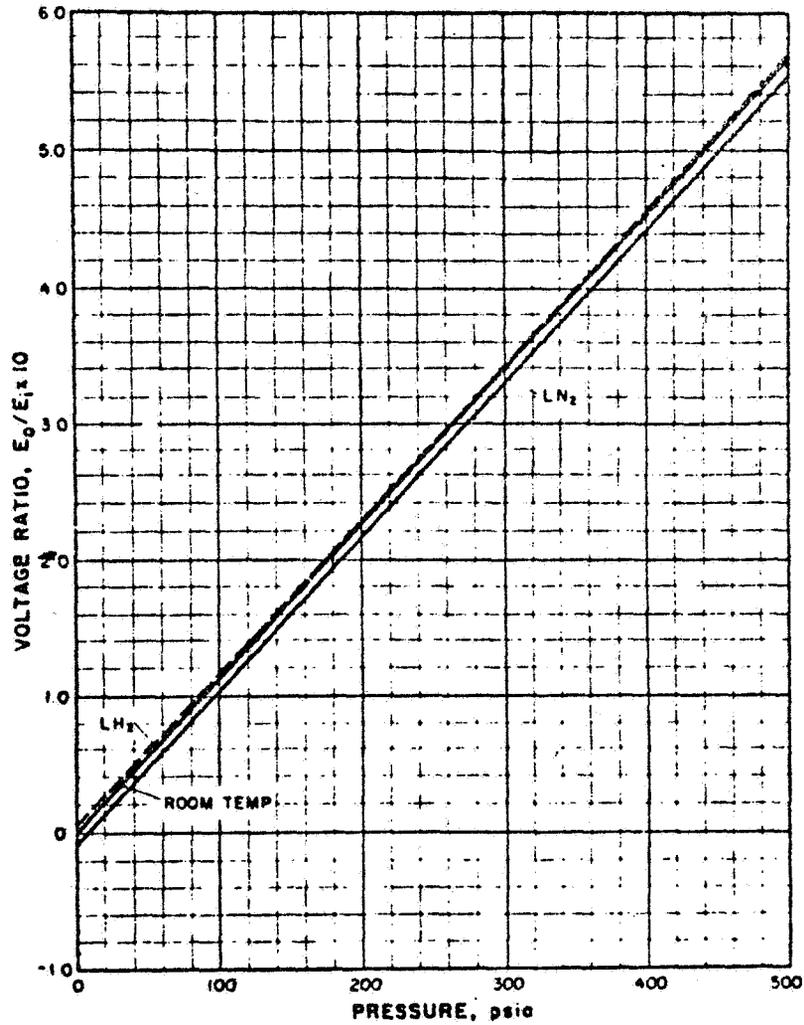


Figure 3.4.3.4-10 [17] Unbonded Strain Gage Type B. Pressure Range 0-500 PSIA After Thermal Cycling

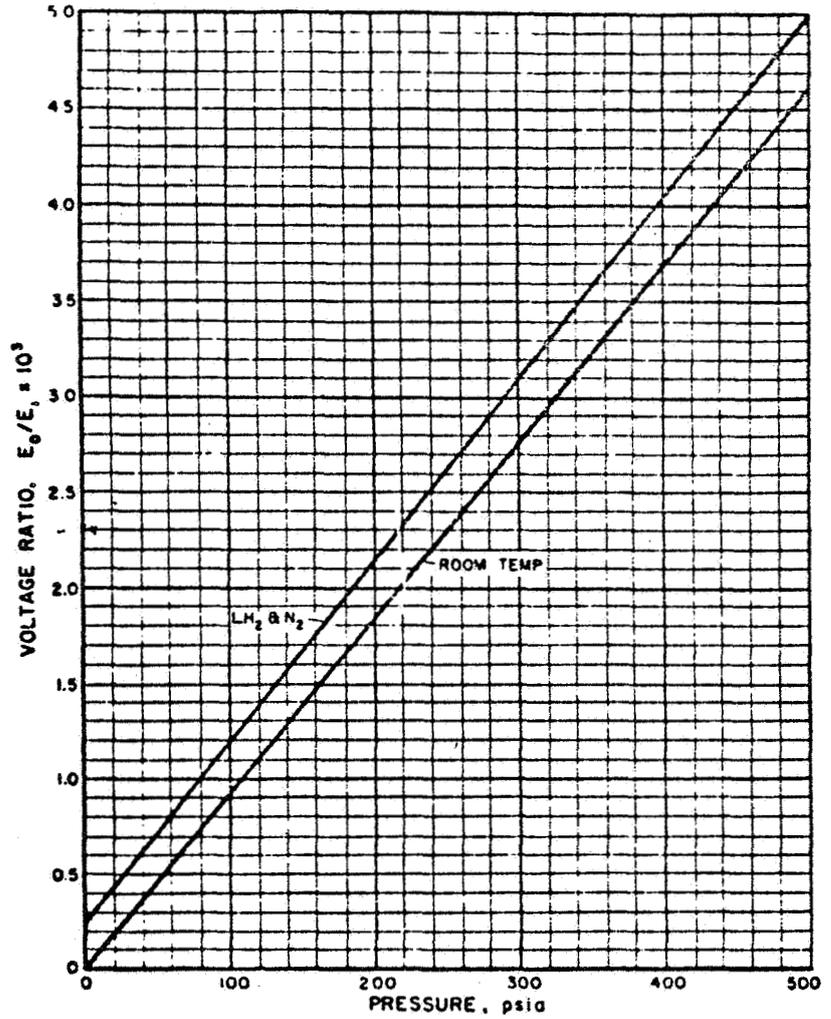


Figure 3.4.3.4-11 ¹⁷ Unbonded Strain Gage Type C. Pressure Range 0-500 PSIA

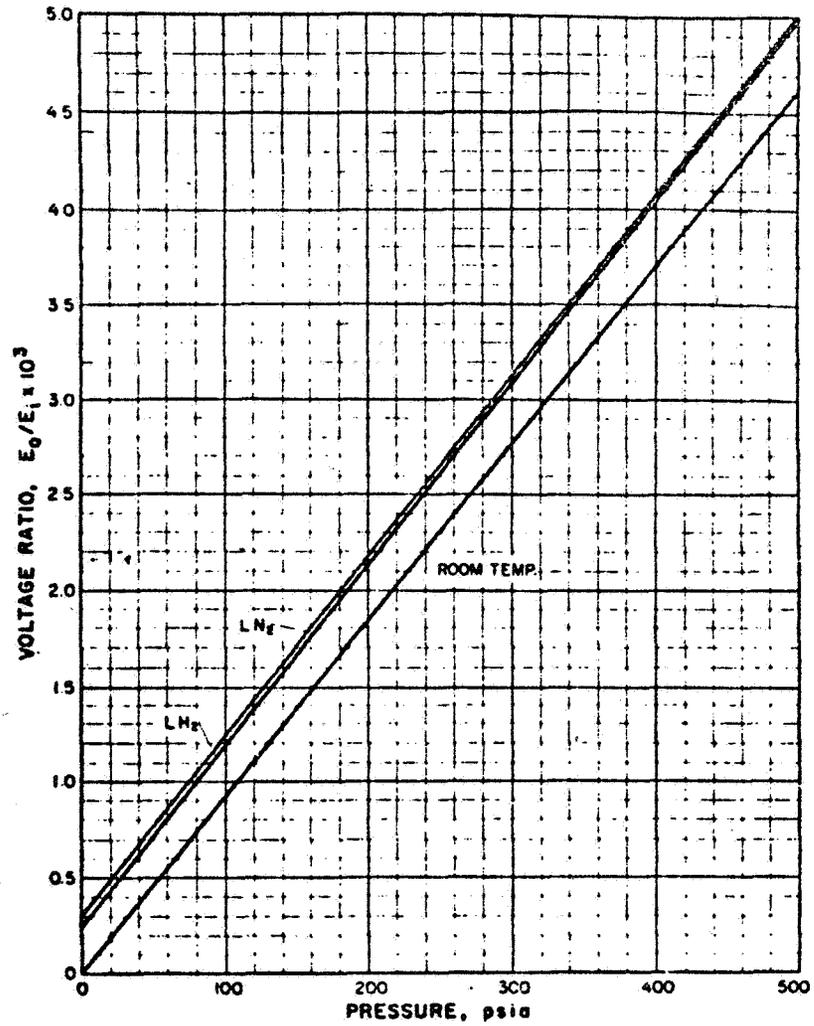


Figure 3.4.3.4-12. Unbonded Strain Gage Type C. Pressure Range 0-500 PSIA After Thermal Cycling

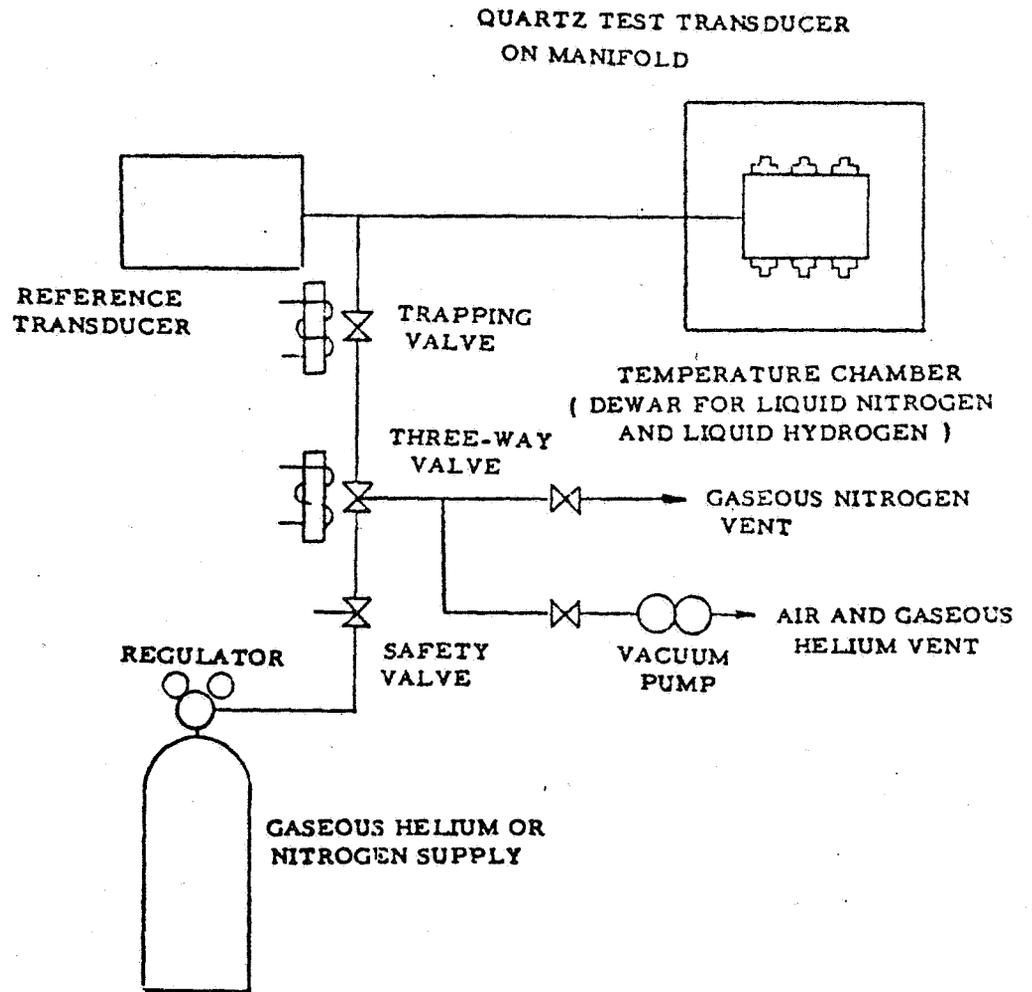


Figure 3.4.3.5-1 [9] Schematic Drawing of Pneumatic System

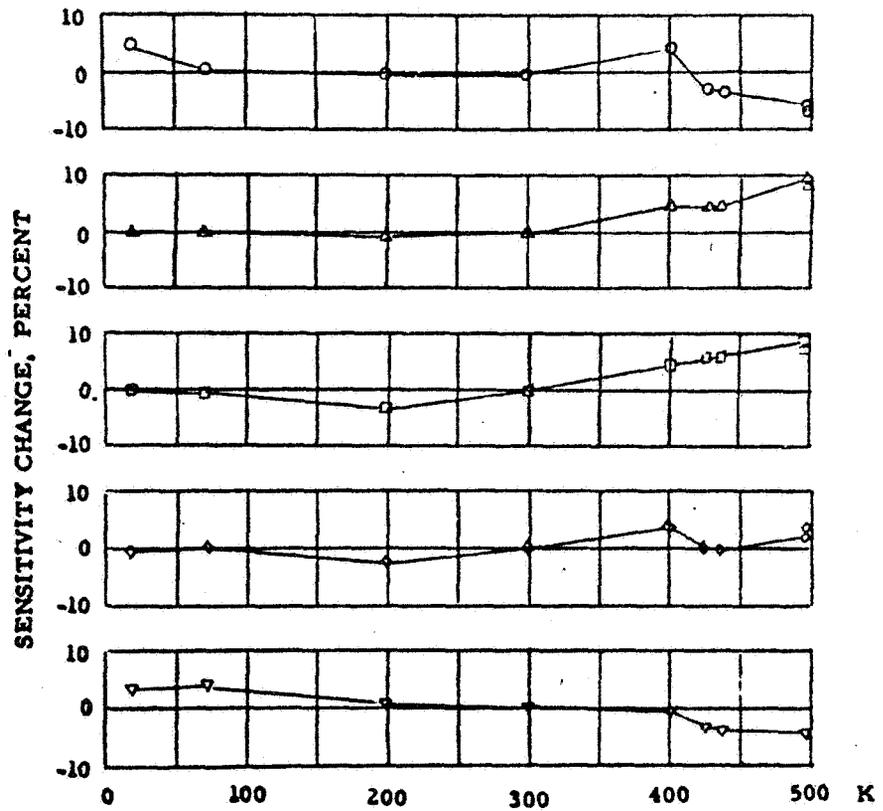


Figure 3.4.3.5-2 Quartz Piezoelectric Pressure Transducer Sensitivity Change (Room Temperature Reference) as Function of Temperature for Five Transducers

The sensitivity at 20K was no more than four percent different from that at room temperature.

The sensitivity at 477 K was no more than nine percent different from that at room temperature.

The day-to-day repeatability of the data at 477 K was within ± 0.5 percent PSO and within one-tenth of this at 20K.

The change in room temperature sensitivity caused by large temperature excursion cycles was negligible.

The last finding is worthy of note for many of the transient response measurements. The conclusion reached by Canfil and Nieberding is that piezoelectric transducers appear particularly good for low-temperature applications..

It should be pointed out that the test procedure utilized for this investigation is equivalent to a uniform steady-state temperature environment. This test does not establish the gradient condition of the previous two studies. As was pointed out earlier, piezoelectric transducers should not be as sensitive to gradients as the temperature compensated strain gage instruments since no compensation components are used. The unknown factor is the strain effects on sensitivity due to uneven temperature distribution throughout the body of the instrument. The smallness of these transducers should help in alleviating this problem by adequate insulation designs. It is quite possible the piezoelectric pressure transducer is the most accurate instrument available on the market today for the measurement of cryogenic pressure fluctuations in a close-coupled application operated in a transient temperature environment.

Piezoelectric transducers cannot be utilized in the application of most static pressure measurements; however, it is capable of measuring higher frequencies with greater accuracy over a wider range of pressure levels than any other current designs. As the authors of the Lewis Research Center report point out, a typical piezoelectric transducer coupled with a charge amplifier is capable of measuring from less than 0.1 Hertz to tens of kilohertz and over a range of full-scale pressures differing by a factor of 1000 with a constant accuracy.

3.4.3.6 Thermal Shock Tests

Another instrument type not discussed in much detail to this point is the potentiometric type pressure transducer. This investigation has uncovered only a single source for this design available as an off-the-shelf item.

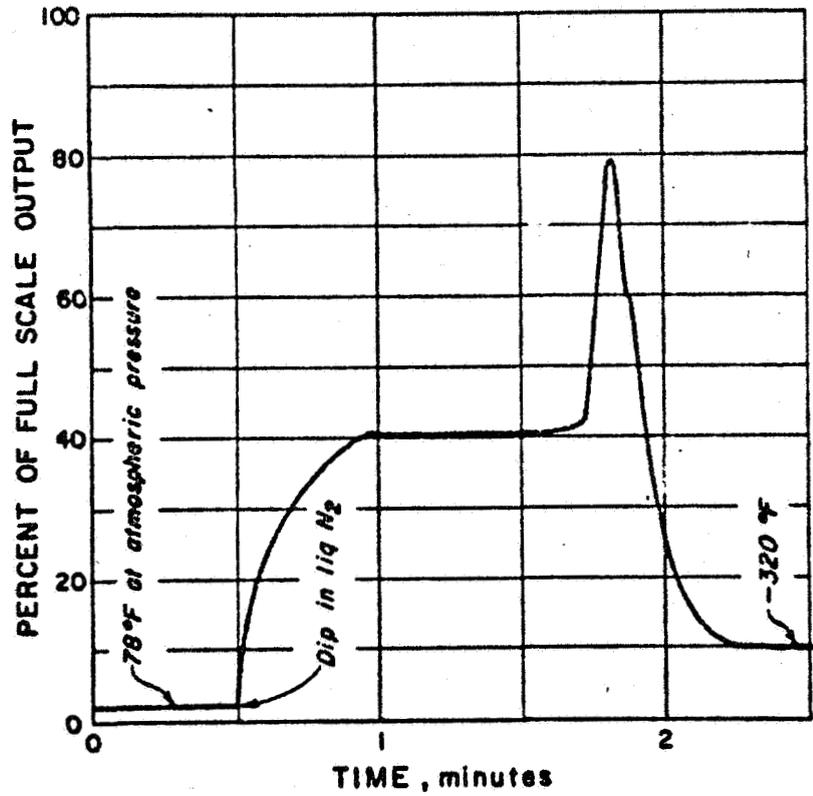
It should be noted that the Bourns instrument identified in this study does not incorporate a temperature compensation resistor. This feature should eliminate the same gradient error source seen on temperature compensated strain gage designs. Normally, potentiometric pressure transducers cannot be expected to perform exceptionally well under environmental extremes of vibration and temperature for the reasons explained earlier in the description of these devices.

Table 3.4.3.6-1 [20] Pressure Transducer Specifications

Manufacturer	Model	Pressure Range psia	Compensated Temperature Range F	Temperature Error Band %FR	Nominal Sensitivity mV FR	Nominal Accuracy
CBC	4-313	500	-65 to +1250	--	20	.75
	Unbonded Strain Gage					
CBC	4-354	500	-320 to +250	5.7	20	--
	Unbonded Strain Gage					
Statham	PA-226TC	500	-425 to +14	4	20	1.0
	Unbonded Strain Gage					
Bytrix	HF	125	-65 to +300	3.6	100	1.0
	Silicon					
Schaevitz	P-478	300	-85 to +350	4.3	--	1.0
	LVDI					
Fairchild	Potentiometer 947-3000	1000	--	--	--	2.0

Table 3.4.3.6-2. [20] Temperature Errors

Manufacturer	Type	Model	Transient Error Band % FR	Maximum Transient Error % FR	Steady-State Error at -320F % FR	Time to Steady-State Minutes
CBC	Unbonded Strain Gage	4-313	80	+80	+10	1.8
CBC	Unbonded Strain Gage	4-354	18	+13	+1	1.8
Statham	Unbonded Strain Gage	PA-226TC	16	+12	+1	2.5
Bytrix	Silicon Strain Gage	HF	98	+80	+80	0.5
Schaevitz	LVDT	P-478	58	-50	-50	4.5
Fairchild	Potentiometer	947-3000	10	+10	+10	1.5



20

Figure 3.4.3.6-1 Thermal Shock Test of CEC 4-313 Pressure Transducer

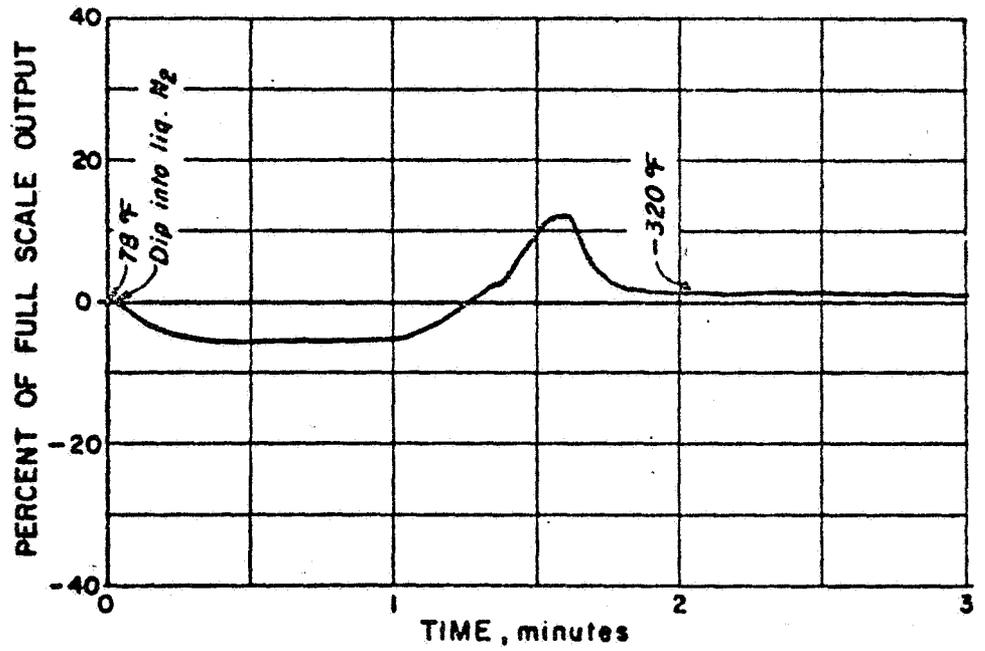
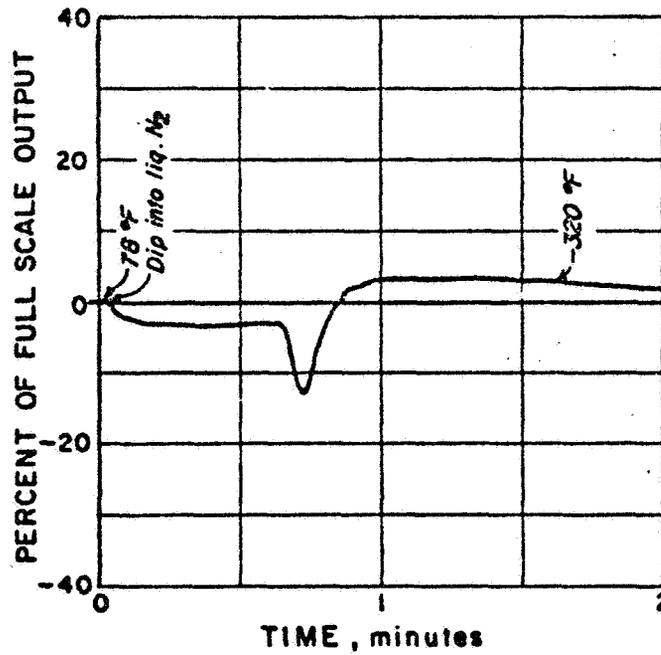
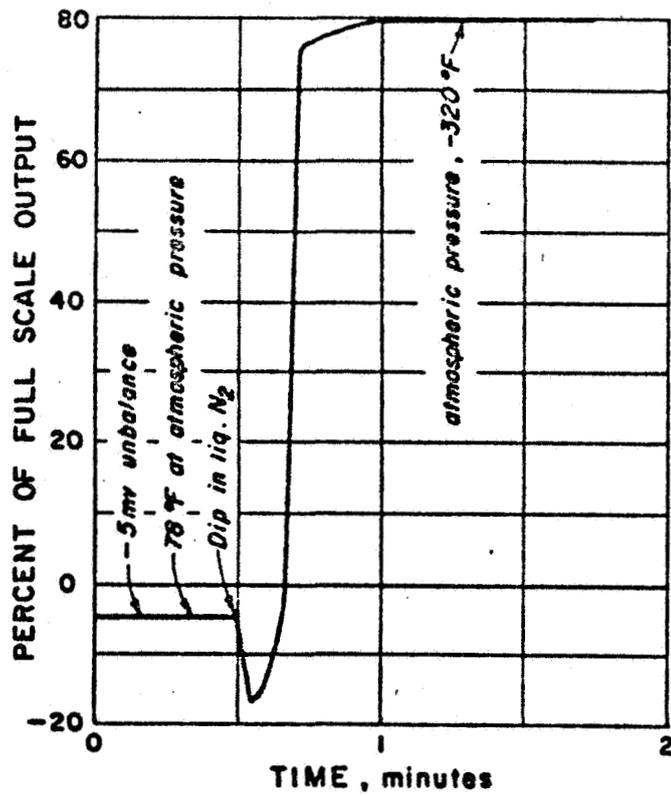


Figure 3.4.3.6-2 Thermal Shock Test of CEC 4-354 Pressure Transducer

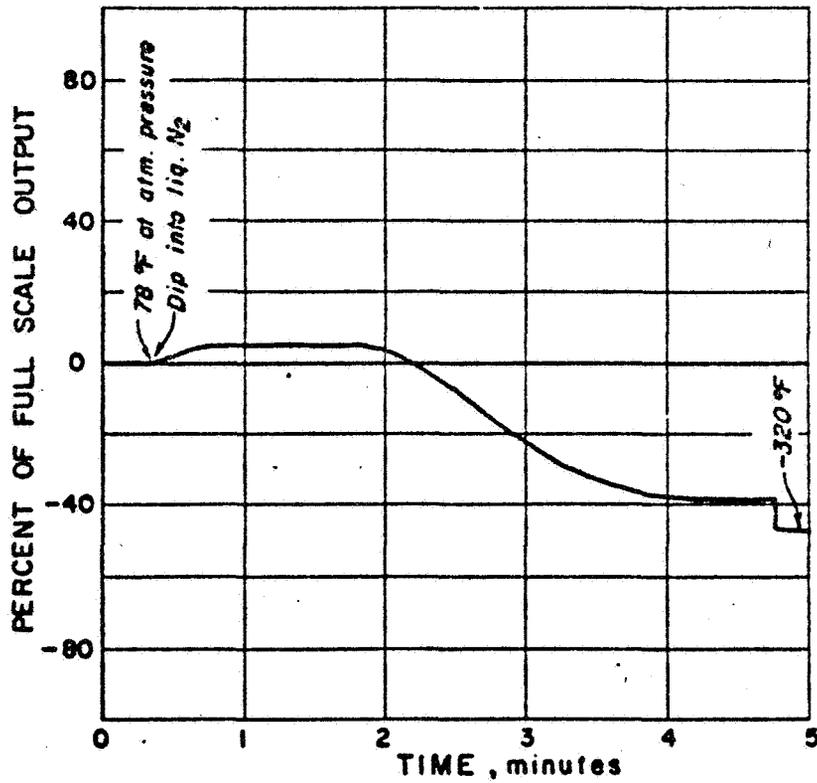


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Figure 3.4.3.6-3 Thermal Shock Test of Statham PA226TC Pressure Transducer.

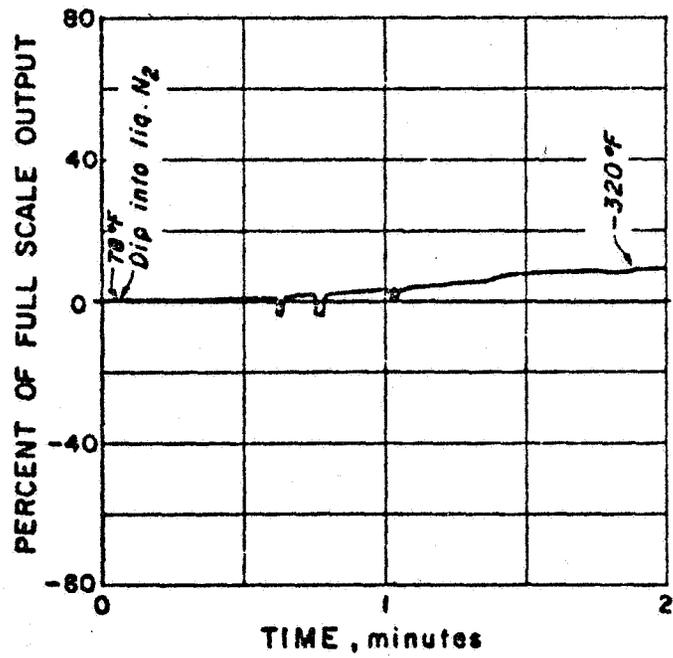


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Figure 3.4.3.6-4 Thermal Shock Test of Bytrix HF125 Pressure Transducer



28
Figure 3.4.3.6-5 Thermal Shock Test of Schaevitz P478 Pressure Transducer



[2]
Figure 3.4.3.6-6 Thermal Shock Test of Fairchild 947-3000 Pressure Transducer

In a test program conducted at the Cryogenic Engineering Laboratory of the National Bureau of Standards by Mr. J. W. Dean [20], room temperature transducers were plunged into a bath of liquid nitrogen. Transient and steady-state outputs of each transducer were recorded throughout the test with a reference atmosphere pressure applied. The results of this test were surprising in that the potentiometric instrument performed with the smallest transient temperature error band when subjected to the severe temperature shock of this test. The results for each test specimen transducer are provided in Tables 3.4.3.6-1 and 3.4.3.6-2, and Figures 3.4.3.6-1 through 3.4.3.6-6.

It must be concluded that the same temperature gradient problems seen in previous tests were seen during this test to cause the strain gage units to exhibit large error values. The significant point made apparent by this test is that the potentiometric transducer exhibited a maximum error of ten percent FSO. This result indicates that a potentiometric transducer could be installed in a cryogenic transfer line without regard to temperature stabilization and still provide a measurement accurate to ± 10 percent FSO. Further accuracy improvements might be expected with transducer calibration performed under conditions simulating the measurement environment.

No correlation can be made for the potentiometric unit tested in the NBS investigation with the Bourns unit of this evaluation since considerable differences exist between manufacturers. There does appear to be a correlation with the results of the NBS test unit with the potentiometric unit tested by Kinzie and Murphy. In the Kinzie and Murphy test, the two transducers tested under OAE conditions exhibited a maximum of 7.5 and 12.3 percent FSO apparent pressure error. The values are close enough to the NBS test to offer some indication of the error magnitude which can be expected. Static calibration tests under uniform steady state conditions indicate that the Bourns unit exhibits less than a four percent difference from an ambient calibration run.

3.5 CONCLUSIONS

This investigation had the objective of locating a pressure transducer capable of a measurement accuracy of two percent full-scale output under any of the transient cryogenic temperature and pressure conditions which could be encountered in a space vehicle application. It was recognized at the onset of this study that this problem was more complex than merely conducting a search for a manufacturer's part advertised to meet the two percent accuracy requirement. Researchers have uncovered many cases where the performance results indicate the complexity of making these measurements. The performance of transducers shows a wide variation between instruments and instrument types, but certain facts have been established by investigators which provide clues for design engineers on the proper selection and use of transducers for specific measurement conditions.

A review of the research work discussed in this report reveals several important facts or trends established from test results, analysis and findings. Horn's tests revealed the importance of thermal gradients as an error contributing source. Kinzie and Murphy verified the importance of the location of the temperature compensation resistors in strain gage transducers and they identified the error characteristics of transducers under specific temperature exposure conditions. Dean and Flynn's analysis established the potential error



magnitude due to expansivity and Young's modulus temperature coefficients. The Princeton study pointed out the importance of the flush diaphragm transducer for making high frequency response measurements accurately. The NBS study by Smelser identified the merits of the strain gage pressure transducers for cryogenic measurements and the Lewis Research Report pointed out the special performance capability of the piezoelectric transducer. Dean established the limitation of a potentiometric transducer for cryogenic service. The results of these investigations identify techniques, designs and applications which lead to the best utilization of existing instrumentation or identify design features found to be advantageous for a new design transducer.

The principle error sources found by the investigators are the temperature gradient across the body of the transducer, the change of Young's Modulus coefficient and the necessity of a flush diaphragm for high response measurements. Temperature gradient effects can be minimized by relocating the compensation resistors in the same thermal environment as the strain gages and by selecting materials and designs which minimize thermal gradients and thermal gradient effects. Insulation of the transducer further reduces external environmental effects and tends to stabilize transducer body temperatures to a uniform value. Provision for Young's Modulus coefficient change can be minimized by calibration procedures suitable to the using condition and by bridge circuit compensation techniques. Practically all manufacturers calibrate their instruments under a uniform steady-state temperature condition. This fact is not surprising, since the cryogenic application provides an infinite number of possible environments and a closed flowing cryogenic system is hazardous as well as expensive to operate. The problem resulting from this calibration procedure is that in field applications a uniform steady state environment rarely exists. The common application is one where a temperature gradient occurs across the body of the transducer with the front face being much colder than the aft face.

Researchers provide substantial evidence that temperature gradients result in the single most important error source for transducers, especially on instruments which incorporate temperature compensation resistors as most strain gage pressure transducers do. An important first step in obtaining transducers capable of accurate measurements under transient temperature and pressure environments is to reduce the gradient environment or to utilize the gradient in the calibration procedure. In the first case, insulating the transducer to minimize external environmental influences is one approach. This procedure would be most effective in applications where the transducer is at or near the cryogenic temperature, and pressure fluctuations do not result in temperature variations much beyond the cryogenic range. Such a measurement would be like D266-206 (LOX sump pressure) (See Figure 3.2-3). The tank liquid provides a near infinite cold source and if the transducer is close-coupled to the sense port and carefully insulated from the external environment, it should operate within a narrow temperature band near the cryogen temperature. If the transducer for this application is calibrated at the cryogen temperature either with the transducer at a uniform and steady-state temperature or under a condition simulating the actual installation environment, little temperature sensitivity error should result. The degree of accuracy required would dictate the degree of precision in duplicating the actual using condition.



Unfortunately, most measurements present a more difficult environment than the LOX sump measurement. In almost every case, the object of attempting to maintain a uniform and steady state temperature of the transducer can better be achieved by carefully insulating the transducer to reduce the influence of the external environment. Each application, however, must be evaluated individually. The decision to insulate or not to insulate and even the degree of insulation must be based on the design goal of attempting to minimize temperature gradients across the body of the transducer.

A second approach is to calibrate instruments under the same temperature conditions as the using environments. The degree of simulating the actual temperature environment depends greatly upon the transient condition and the range of temperature which occurs. If there are rapid and wide temperature and pressure fluctuations, little can be done to simulate this environment during the calibration procedure. If the actual using environment remains relatively constant or an occasional transient occurs, this condition can be simulated in the calibration procedure. In any case, almost any attempt to duplicate a using environment during the transducer calibration should lead to more accurate results than the procedures used currently of calibrating instruments under a uniform steady-state temperature environment.

In an application where temperature fluctuations occur as a short-duration transient, such as in a feedline where a valve is suddenly opened to admit the cryogen, the use of a transducer with the inlet port which has a diffuser protected cavity performed better than other designs during the initial several minutes after exposure to the cryogen. In the Kinzie and Murphy test program, three transducers provided by one supplier performed better than any other instruments tested. The authors found after disassembly of the three test specimen transducers that the units were constructed to isolate the interior of the transducer as thoroughly as possible from transient temperature conditions in both the pressurant fluid and the overall environment exposure conditions. The transducer with heavy wall construction of the case provides a relatively large thermal mass and tends to smooth out temperature variations which would otherwise affect the electrical system. Another design feature of this transducer was that the strain gages were installed on the deflection beam instead of directly on the diaphragm which provided additional protection against diaphragm temperature variations. The diaphragm was also protected by a tube-and-cavity design with a large porous diffuser in the cavity inlet tube.

The use of this type of transducer seems to hold promise for measurements where an infrequent pressure-temperature transient occurs over a short duration of no more than several minutes. There are, however, several potential problems to consider.

The transducer performed well with respect to the apparent pressure test because of the thermal mass associated with the heavy wall construction which tended to smooth out the temperature variation which could affect the electrical system. This very fact may be an error source for the measurement. Assuming a condition where the transducer walls act as a heat source, it follows that the boiling of the cryogen takes place when a sudden surge of pressure occurs by introducing the cryogen into the transducer diffuser and cavity area. If the actual

response of the transducer with respect to phase and amplitude were monitored closely during the transient period, it would most likely be found that there is considerable distortion in the measurement with respect to the reference source. The evaluation of transducers for these performance parameters can only be accomplished by a dynamic response test.

At the Guggenheim Laboratories for Aerospace Propulsion Science at the Princeton University, [21] a survey was conducted to establish the need for transient pressure measurements in present and future liquid propellant rocket systems, and research was performed that would foster the development of advanced transducers for making such measurements. Quotations taken from the report are presented in the following text to emphasize the fact that any connecting tubing or other voids or chambers between the sensing element, of the transducer and the measurand will degrade the measurements results to some extent.

"The fundamentals of vibratory motion of an elastic system, such as a transducer, and of an acoustic system, such as any connecting fluid-filled passage, must be kept clearly in mind to understand the dynamic response of transient pressure measurement systems. When pressure variations have a relatively slow rate of change, almost any system will display an output that follows the change in pressure very closely. As the rate increases, even specially designed systems will respond dynamically and will no longer represent the higher frequency inputs with fidelity in either amplitude or phase."

"To obtain the utmost fidelity in the measurement of transient pressures, the sensitive element of the transducer, usually a diaphragm, must be mounted flush with the wall of the chamber in which the pressure transients are occurring."

Thus the evidence provided by researchers establishes the fact that for high response pressure changes only the flush diaphragm transducer configuration should be considered where maximum accuracy is required. The transducer types which lend themselves to high frequency measurements are the strain gage and quartz crystal transducers. Of those two the piezoelectric transducers are limited to dynamic response measurements only; therefore, where a single transducer is required for the measurement of both static and dynamic responses, the strain gage transducer is the only good compromise available.

Perhaps the most significant point made apparent by the investigations of researchers was that the temperature compensation resistors were the largest contributor to temperature sensitivity error when they were not located in the same thermal environment as the strain gages. The survey of manufacturers' parts revealed that all of the suppliers of this investigation located these compensating resistors near the connector end of the transducer. Several good reasons are apparent for this procedure; however, the transducer becomes highly susceptible to thermal gradients. A significant step toward correcting temperature sensitivity errors would be to locate the compensation resistors in the same thermal environment as the strain gages. All of the researchers who have identified this problem appear unanimous on their recommendations for this change.

Further evidence from research work provides information that the greatest error in pressure measurements occurs during the initial period immediately following the exposure of the transducer to the cryogenic media such as may occur after a pressure surge in the system. This fact points out the findings that the uneven temperature distribution within the diaphragm, the case and the compensation resistors are the major source for the transducer error. This fact verifies the conclusion that a transducer capable of reaching a uniform temperature rapidly will reach a stabilized output rapidly.

An ideal transducer design is one which has an infinitely small mass which has the capability of following temperature fluctuations nearly instantaneously. Such a design, of course, is impossible to create and the designer can only approach this design goal with a transducer which has a minimum thermal mass and small size.

In addition to the thermal mass of the transducer, heat transfer properties and the coefficient of expansion of transducer materials play an important influence in minimizing thermal stresses of transducer components. Good design practices for transducers utilized in temperature extremes, provide for the optimum heat transfer and equal expansion coefficients for critical sensor components. These design characteristics are achieved by providing heat transfer paths in keeping with a desired result such as providing uniform heat paths for uniform temperature distribution or adjusting the cross-sectional area for a non-uniform distribution. Surface areas of the components provide another area for consideration. Component expansion and contraction compatibility problems are usually resolved by the selection of common or similar materials for the critical sensor components. The Kinzie and Murphy investigation points out the error resulting from diaphragm distortion effects and thus provides a case for concluding the advantage for relatively thick diaphragms or even diaphragms machined integral with the case. The thick diaphragm design is, of course, contrary to a low thermal mass design and this would be an area where a design tradeoff would be made based on test results.

Another highly desirable design goal which aids the thermal gradient problem is to reduce the length of the transducer, since thermal gradients result from temperature differentials and the temperature differential is a function of the distance from the cold source to the point of interest.

3.6 RECOMMENDATIONS

For a transducer capable of meeting the temperature sensitivity goal of this investigation and which is small and capable of both steady-state and high frequency response measurements, the recommendation is made that a new transducer be developed. The new transducer design should incorporate all of the desirable design characteristics found by researchers. These are:

- a. Flush diaphragm design with diaphragm machined integral with the case.
- b. Small case size with short body length and low thermal mass.
- c. Strain gage design with gages mechanically coupled to the diaphragm in an unbonded configuration

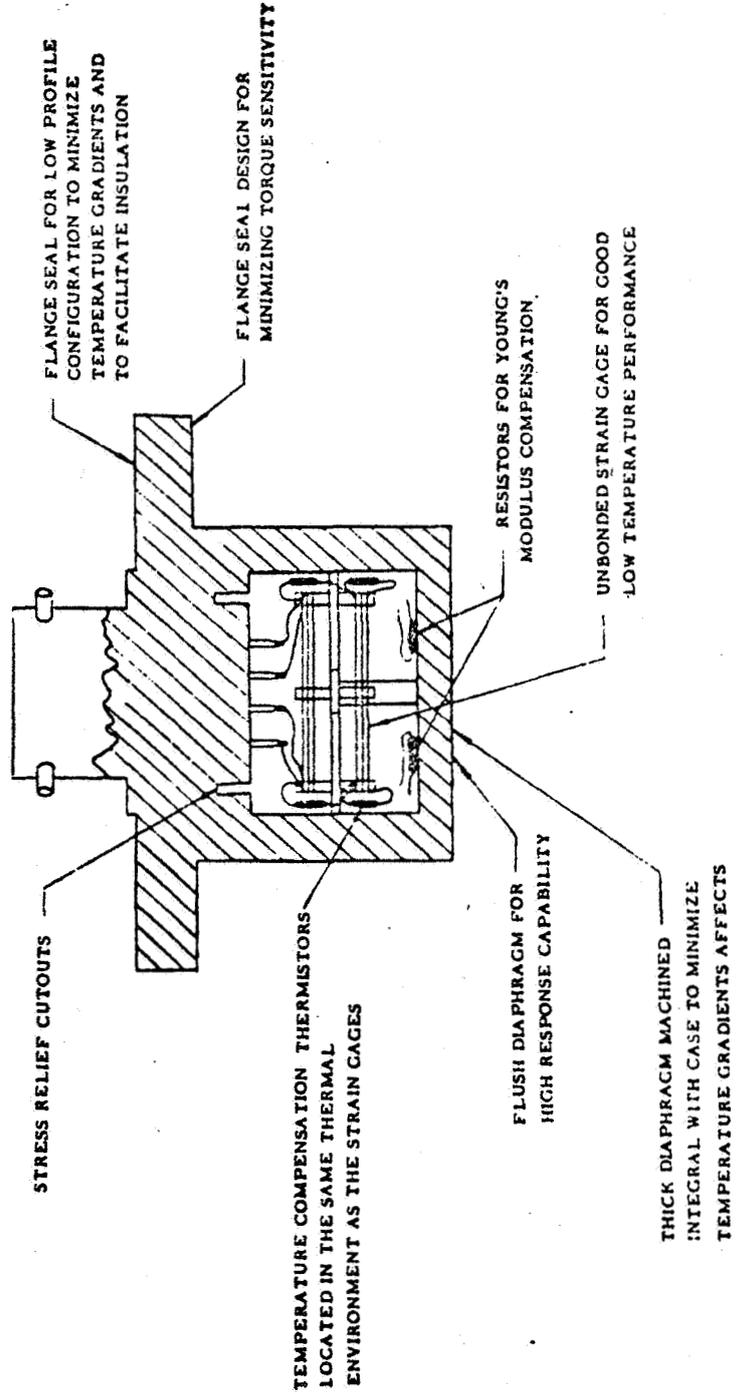


Figure 3.6-1 Pictorial Representation of Pressure Transducer Incorporating Known Desirable Features for Cryogenic Applications



Table 3.6-1 Generalized Measurement Functions with Recommended Transducer Type and Application Provisions for a Measurand of LOX or LH₂

GENERALIZED MEASUREMENT FUNCTION	TEMPERATURE PROFILE	RECOMMENDED TRANSDUCER TYPE	APPLICATION PROVISIONS	RECOMMENDED CALIBRATION PROCEDURE	ESTIMATED TRANSDUCER INACCURACY (% F.S.)
APPLICATION: MEASUREMENT OF LOX OR LH ₂ TANK RESERVOIR PRESSURE PRESSURE PROFILE: STEADY OR SLOW CHANGING APPROXIMATE RANGE: 0 TO 100 PSIA	LOX OR LH ₂ AT SENSE PORT	1. STRAIN GAGE DESIGN EITHER FLUSH DIAPHRAGM OR CAVITY 2. POTENTIOMETRIC	1. CLOSE-COUPLED AND INSULATED 2. REMOTE INSTALLATION	1.4. USING CONDITION OR IMMERSED IN LH ₂ 1.5. AT OPERATIONAL TEMPERATURE 2. AT OPERATIONAL TEMPERATURE	1.4. 1.0 to 2.5 1.5. 1.0 to 2.0 2. 2.0 to 3.0
APPLICATION: MEASUREMENT OF LOX OR LH ₂ FEEDLINE PRESSURE PRESSURE PROFILE: STEADY STATE TO SLOW ACTING FLUCTUATIONS APPROXIMATE RANGE: 0 TO 100 PSIA	TRANSDUCER FRONT FACE EXPOSED TO CRYOGEN, AFT BODY EXPOSED TO AMBIENT ENVIRONMENT, CONVECTIVE COOLING TAKES PLACE DURING FLOW.	STRAIN GAGE DESIGN EITHER FLUSH DIAPHRAGM OR CAVITY	CLOSE-COUPLED AND INSULATED	1.4. CALIBRATE UNDER USING CONDITION 1.5. CALIBRATE IMMERSED IN LH ₂	1.4. 1.0 to 3.0 1.5. 2.0 to 4.0
APPLICATION: MEASUREMENT OF LOX OR LH ₂ FEEDLINE PRESSURE USING SINGLE TRANSDUCER PRESSURE PROFILE: STEADY STATE TO FAST ACTING FLUCTUATIONS APPROXIMATE RANGE: 0 TO 100 PSIA	TRANSDUCER FRONT FACE EXPOSED TO CRYOGEN, AFT BODY EXPOSED TO AMBIENT ENVIRONMENT, CONVECTIVE COOLING TAKES PLACE DURING FLOW	STRAIN GAGE DESIGN WITH FLUSH DIAPHRAGM	CLOSE-COUPLED AND INSULATED	CALIBRATE AT USING TEMPERATURE	2.0 to 10.0 OR GREATER
APPLICATION: MEASUREMENT OF LOX OR LH ₂ FEEDLINE PRESSURE USING TWO TRANSDUCERS PRESSURE PROFILE: STEADY STATE TO FAST ACTING FLUCTUATIONS APPROXIMATE RANGE: 0 TO 100 PSIA	TRANSDUCER FRONT FACE EXPOSED TO CRYOGEN, AFT BODY EXPOSED TO AMBIENT ENVIRONMENT, CONVECTIVE COOLING TAKES PLACE DURING FLOW.	1. CRYSTAL TRANSDUCER FLUSH DIAPHRAGM FOR DYNAMIC RESPONSE MEASUREMENTS. 2. STRAIN GAGE TRANSDUCER FOR STEADY STATE PRESSURES.	1. CLOSE-COUPLED AND INSULATED 2. REMOTE INSTALLATION	1. CALIBRATE IMMERSED IN LH ₂ ON USING LIQUID 2. CALIBRATE AT OPERATIONAL TEMPERATURE	1. 2.0 to 5.0 2. 1.0 to 2.0





- d. Temperature compensation circuitry located in the same thermal environment as the strain gages.
- e. Transducer installation provisions which facilitate insulation provisions and minimize thermal gradients.

Figure 3.6-1 represents a configuration which incorporates these desirable characteristics.

For measurements requiring the best possible accuracy obtainable under the current state-of-the-art for both dynamic and steady-state responses, the use of two transducers is recommended as the solution. With this design approach, a close-coupled transducer installed on the pressure port would measure the dynamic responses and a remote transducer installed at the end of a sense line measures the static pressure levels. The advantage for this design approach is that the remote transducer can be protected from temperature transients; thus it is less susceptible to large-scale errors. Secondly, for this type of installation the piezoelectric transducer design lends itself especially well for monitoring the dynamic responses. Since the piezoelectric device does not respond to static pressure levels, it is not susceptible to zero shift errors. For high frequency pressure measurements, the crystal pressure transducer offers more desirable features than any other design available today.

Table 3.6-1 summarizes recommendations for transducer types and application provisions for four generalized measurements. The recommendations are based on currently available equipment. The expected accuracies specified are estimates.

3.7 Survey of New Designs in Work

The results of the inquiry submitted to manufacturers reveals that virtually no research and development activity is being conducted for the development of new designs specifically for cryogenic space service. The investigation has uncovered at least two cases where NASA-sponsored programs have generated activity in the past. The first reference source, [22] describes the activity over a period April 1965 through October 1967 for a program entitled "Study and Investigation, Design, Development and Fabrication of a Cryogenic Pressure Transducer." The second reference source [23] is a recent proposal for a flange-mounted absolute pressure transducer designed for operation at cryogenic temperatures. No attempt will be made to describe either effort, since the work was accomplished under NASA sponsorship.

With respect to currently available designs, the thin film deposited strain gage design employed by Statham Instruments, Inc. represents a relatively new approach with cryogenic capability. Statham has developed a low-temperature coefficient deposited gage in addition to maintaining very closely matched gages. Statham reveals that data taken to date have been very promising, and it appears that a ± 2 percent error band to -453 F is within close reach. In addition, transducers are being developed with dual bridges for redundancy. The thin film process lends itself well to the dual bridge design since both bridges are simultaneously deposited on a common substrate.



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As an additional development program, the practicality of experimentally determining temperature compensation elements on the beam to eliminate the transient thermal error is being contemplated.

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4.0 HIGH PRESSURE FLANGE SEAL INVESTIGATION

Consideration of a high pressure (5000 psi) transducer for cryogenic applications whose design concept utilized flanged mounting precipitated this investigation. The flange mounting allows for a low profile envelope thus minimizing temperature gradients and facilitates insulation of the mounting surface. The flange mounting also minimizes torque sensitivity of the transducer mechanism during installation. Adequate sealing of the transducer becomes an important consideration. This investigation primarily addresses itself to the search for a metallic seal to attain optimum sealing for the temperature and pressure application. The size range of such a seal is restricted to seals of 2 inch outside diameter maximum.

4.1 APPLICATION OF HIGH PRESSURE FLANGE SEALS

Usually, flanged connections are loaded by internal pressure that tends to separate the two interfaces. Bolts are preloaded to counteract the separating load and minimize, if not eliminate, separation of the two flanges. The flanges must be sufficiently rigid to carry the separating load with a minimum of deformation.

The seal must provide the required contact intimacy and must also be structurally capable, either by itself or with the flanges, of maintaining contact under all operation conditions.

4.1.1 Series vs Parallel Loading

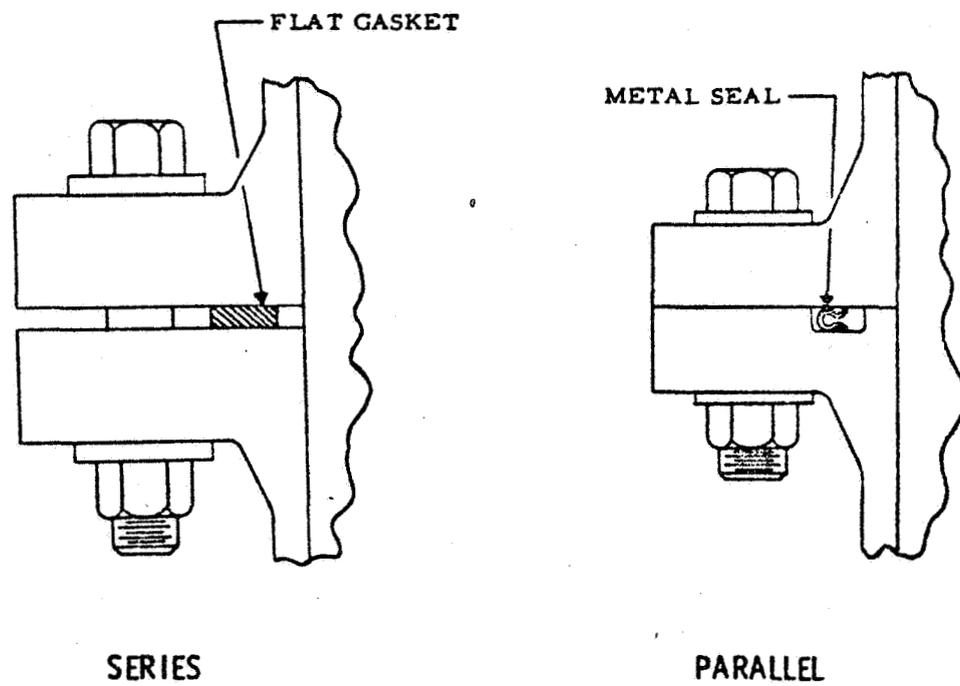
In the series-loaded connector (Figure 4.1.1-1) fastener load is carried entirely through the sealing element, usually a flat gasket. The flanges do not contact each other. Thus, sealing stress depends on initial bolt torque, external loads, and fluid pressure.

A parallel-loaded joint transmits the majority of the bolt load directly through the flange faces: only a small percentage of the load is absorbed by the seal. The required sealing contact stress is obtained by seal deflection, independent of bolt torque and pressure (discounting any pressure energizing effect), and remains constant as long as the flanges are in contact.

4.1.2 Metal to Metal Sealing

Under magnification, irregularities in the smoothest surfaces look like mountains and valleys to a gas molecule. Even when two "flat and smooth" surfaces are in contact with each other, only a small percentage of the surfaces are in intimate contact. Contact can be increased by increasing the load normal to the surfaces, but unless the surfaces are extremely smooth, a large number of leak paths exist.

A more practical approach is to fill the microscopic valleys in the faying surfaces rather than try to flatten the peaks. Most metal seal designs incorporate a soft, deformable coating on the sealing surface. Performance depends upon the degree of contact between the soft seal surface and the hard flange surface.



[24]
FIGURE 4.1 I-1 SERIES AND PARALLEL-LOADED JOINTS. THE JOINT LOAD IS TRANSMITTED THROUGH THE GASKET IN THE SERIES-LOADED JOINT; IN THE PARALLEL JOINT, MOST OF THE LOAD IS CARRIED THROUGH THE FLANGE.

4.2 VARIABLES AFFECTING SEAL QUALITY

The leakage rate for a seal depends on fluid properties, sealing surface topography, pressure differential, hardness of the sealing material, and sealing contact stress. The nature of the media to be sealed is dictated by the application; the variables are the specific seal to be used and the flange surface finish.

4.2.1 Surface Topography

Five parameters completely describe a flange sealing surface. They are roughness, flatness, waviness, lay, and discontinuities. Whereas all influence sealing performance, roughness, lay, and discontinuities are the most important.

Roughness is the microscopic peak and valley deviation from an average. A smoother finish improves performance, but increases the cost. A 32 micro-inch (M in.) finish is considered the most practical compromise.

Lay, which is the direction of tool marks, may be unidirectional, multi-directional, radial, or circumferential, depending on the manufacturing method. Turning is the most practical method of machining a flange surface and usually results in a circular lay which is also ideal from a sealing standpoint. If a surface cannot be machined with a circular lay, it must be made smoother to obtain the same performance. For example, a 32M in. circular lay is sometimes considered the equivalent of an 8M in. multi-lateral finish. The strong effect of lay upon sealing is illustrated in Table 4.2.1-1.

Discontinuities on a sealing surface will increase susceptibility to leakage. Nicks, scratches, or severe dips should be explicitly disallowed on the engineering drawing.

The seating load and the contact area determines the contact stress. Deformation of the coating is determined by the yield strength of the coating material.

4.3 DESIGN CONSIDERATIONS

The most important design considerations are pressure, temperature, and type of fluid sealed. These parameters determine the bolting torque, flange thickness, and materials. Since the bolts must lie outside the wall of the duct or pressure vessel, there is usually enough room left over inside the bolt circle for a resilient metal seal. Other factors which may influence the overall flange seal design are:

- a. Ease of assembly and disassembly.
- b. Cost of initial fabrication or subsequent repair.
- c. Provision for checking leaks from the assembled joint.



Table 4.2.1-1 (2) Effect of Surface Finish on Leakage

Surface Finish Roughness (rms)	Lay	Contact Stress Ratio*
4	Random	1.96
40	Radial	2.75
100	Circular	1.46
300	Circular	1.96

*Contact stress/yield strength of sealing material; value required to achieve leakage of less than 10^{-6} scc/sec.

- d. Interchangeability of several types of seals in the event that the first choice is unsatisfactory.
- e. Weight
- f. Allowable leakage: An obvious, but often ignored, consideration, allowable leakage frequently dictates the type of seal coating and surface finish required on the flanges.
- g. Standardization: If the connectors and seals are standardized for a system, joint design is reduced to simply sizing the flanges and bolting. Many systems, however, involve a wide range of environmental conditions and no seal design can be optimum for all applications.

4.3.1 Factors Affecting Performance.

Ultimately, all that matters is whether or not the seal prevents leakage. Sealing must be accomplished with a minimum compromise to the overall design. Thus, other performance parameters must be considered.

Leakage is the criterion most difficult to predict without tests. Many metal seals are capable of achieving leakage rates below measurable levels; however, the penalty in flange loading, extremely smooth finishes or loss of recovery, may be prohibitive. For extremely low leakage rates (less than 10^{-8} scc/sec), an all-metal seal is usually required.

Seating load is an important parameter in flanged connections. The lower it is, the smaller the required flanges and bolting. Also, as seating load is reduced, recovery is increased. Seating load is normally expressed in pounds per inch (lb/in.) of seal circumference and may range from 100 to 500 lb/in., depending on the design.

Recovery of a seal is the elastic springback from a fully deflected position. It is usually less than the total compression of the seal and more than the initial elastic deflection. At least partial plastic deformation is beneficial since the stresses and strains are primarily flexural and, combined with work hardening, result in greater elastic springback than initial elastic deflection. Recovery values of 0.003 to 0.010 inch are typical.

Contact stress at the sealing interface partially determines leakage rate and is a function of seating load and contact area. The pressure differential across the interface, if high enough, may add or subtract significantly from the initial contact stress. Values of 10,000 to 30,000 psi are common.

Pressure compensation, sometimes called pressure energization, pressure actuation, or pressure assistance, is the beneficial effect of pressure upon the seal contact. The geometry of many seals is such that fluid pressure augments the contact stress, thus tending to overcome the increased chance of leakage due to the pressure. But such seals are not actuated by pressure - they will not seal better at high pressure than at low pressure. This is because the pressure effect is negligible except at high pressures - 1000 psi or more. A seal that leaks at 10 psi may be expected to leak as a function

of pressure up to a maximum, then level off and begin to decrease as the pressure effect becomes significant. Depending on the particular geometry, the increase in contact stress due to pressure will range from one-half to three times the pressure difference.

Cavity requirements of the seal in the three basic types of installations are shown in Figure 4.3.1-1. The installation must provide for correct deflection of the seal, location of the seal, structural support for high pressure, and proper surface finish.

To some degree, all these variables depend on the specific seal design selected, but a few generalizations are possible:

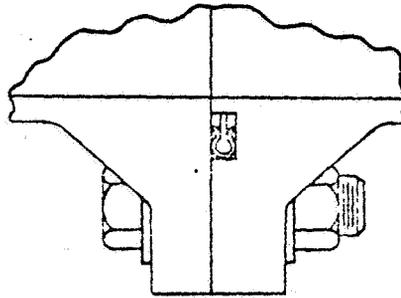
- a. Where a choice exists, specify the largest available seal cross section. Seal cross sections of 1/32 in. should be avoided unless necessary.
- b. For low-volume projects, experimental hardware, and frequently dis-assembled joints, a spacer installation is often most practical. Sealing surfaces are easily prepared and maintained, and different seal designs are adaptable by using a different spacer.
- c. In general, the following surface finishes should be specified:
 1. 8 to 16M in. rms circular lay for vacuum and light gases (He, H₂).
 2. 16 to 32M in. rms circular lay for bubble-tight pneumatic exhaust-gas service.
 3. 32 to 63M in. rms circular lay for liquids and non-critical exhaust-gas service.
- d. A groove installation will usually provide maximum performance as it offers:
 1. A barrier to protect the seal from temperature and fluids.
 2. Maximum outboard location (minimizing interface separation of a seal).
 3. Maximum damage protection of sealing surface.

4.3.2 Materials

The choice of seal materials is usually determined by the operating temperature, although corrosion resistance, fluid compatibility, and radiation effects are also major considerations. Most metal seals contain two materials, a resilient, basic-shape metal, and a soft coating.

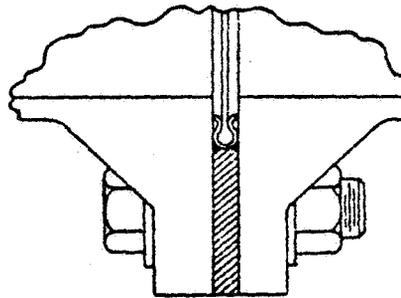
4.3.2.1 Base Material

Seals are highly stressed and must be carefully selected to avoid such problems as stress corrosion cracking, fatigue cracking, low or high-



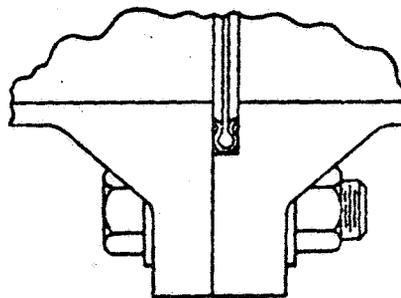
GROOVE

POSITIVE POSITIONING
MINIMUM FLANGE SEPARATION AT SEAL
THERMAL AND FLUID BARRIER
MORE COSTLY TO PREPARE AND REPAIR
SEALING SURFACE PROTECTED FROM DAMAGE



SPACER

MINIMUM FLANGE PREPARATION
EXTRA WEIGHT
LESS POSITIVE POSITIONING
GREATER DESIGN FLEXIBILITY (R&D, TEST, ETC.)
FLANGE REWORK SIMPLE



COUNTERBORE

MINIMUM SPACE
MODERATE COST TO PREPARE AND REPAIR
POSITIVE POSITIONING
SIMPLE SEAL INSTALLATION AND REMOVAL
SEALING SURFACE PROTECTED

[24] FIGURE 4.3.1-1 COMPARISON OF THREE BASIC TYPES OF GLANDS



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Table 4.3.2.1-1 [24] Temperature Limits of Common Seal Materials

<u>Materials</u>	<u>Temperature (Degrees F)</u>
Inconel 718	-423 to +1,400
Inconel X-750	-423 to +1,200
Rene 41	-423 to +1,500
17-4 PH	-100 to +800
A286	-423 to +1,200
304, 321 Stainless	-423 to +800
<u>Coating (See Note)</u>	
Silver	+1,200
Gold	+1,400
Teflon	+ 450
Nickel	+1,800
Copper	+1,200
Indium	+ 200*

*Primarily used for hard-vacuum applications.

Note: Low temperature properties of coating material should be compatible with those of base material on which used.

temperature brittleness, and phase changes. Particular care should be taken when selecting material for a machined metal seal where these problems are increased due to the reduction of properties in the short transverse direction and potential stress risers due to machining discontinuities.

Common base materials fall into one of three basic categories:

- a. Hardenable nickel-base (Inconel 718, Inconel X-750, Rene-41).
- b. Precipitation hardening cres steel (17-4 PH, 17-7 PH, A286).
- c. Austenitic cres steel (302, 304, 321). Commonly used for formed metal seals where work hardening is employed.

High temperature limits of the common base materials are not well defined (See Table 4.3.2.1-1). This is partly due to the fact that a resilient metal seal installed in a parallel-load connector is subject to constant strain, rather than constant stress, and is thus subject to stress relaxation rather than creep due to high temperature. As a function of time, then, the contact stress may be slowly reduced.

As previously mentioned, the initiating contact stress is much higher than the required maintaining contact stress. A large reduction in contact stress due to relaxation in the seal is acceptable. In addition, the temperature level required to cause relaxation in the base material is usually well above the annealing temperature of the plating material. Its yield strength is reduced, increasing the intimacy of contact and improving the seal.

4.3.2.2 Coating Materials

The coating material is usually a pure metal (silver, gold, nickel, or copper) or a plastic dispersion coating such as TFE. Coating materials are chosen on the basis of softness, corrosion resistance, temperature resistance, and cost.

The upper temperature limits of platings are even less well established as that of the base metals, with recommendations ranging from just under their annealing temperature to within 100 F of their melting temperatures, a variation of 1,000 F or more (See Table 4.3.2.1-1).

Unlike the base material, the coating is subject to creep at high temperatures. Unless the coating is very thin (about 0.001 to 0.002 inch) it could conceivably be pushed out at high temperatures and pressures.

4.3.3 Load Analysis

The seal cross section can be treated as a simple cantilever beam with an end load. Assuming substantial plastic deflection, the load-carrying capacity of the seal can be approximated by

$$P = \frac{R}{R - W} \frac{St^2}{4W}$$



where: P = unit sealing load, lb per in. circumference; R = radius of seal ring, in.; W = moment arm, in.; S = ultimate strength of material, psi; and T = thickness at critical section, in.

For seals greater than 1½ in. OD, the R/(P - W) term approaches unity and can be dropped. The equation is not complicated and many simplifying assumptions are made; however, it is useful both for designing seals and evaluating designs.

4.4 TYPES

Resilient metal seals, originally developed for the aerospace industry, are now finding their way into demanding, commercial applications. These seals are most often used in extreme temperatures, or when minimum weight is required.

Resilient metal seals are capable of reducing leakage rates below measurable levels, "zero leakage" for all practical purposes. Under similar conditions, leakage past most other static seals is several orders of magnitude greater.

Unlike flat metal gaskets which have been tested, documented, standardized, and reduced to relatively simple design procedures, experience with resilient metal seals has been gained by "cut-and-try" usage and design is far ahead of analytical techniques. The fundamental sealing phenomenon has only been studied in depth in the last few years.

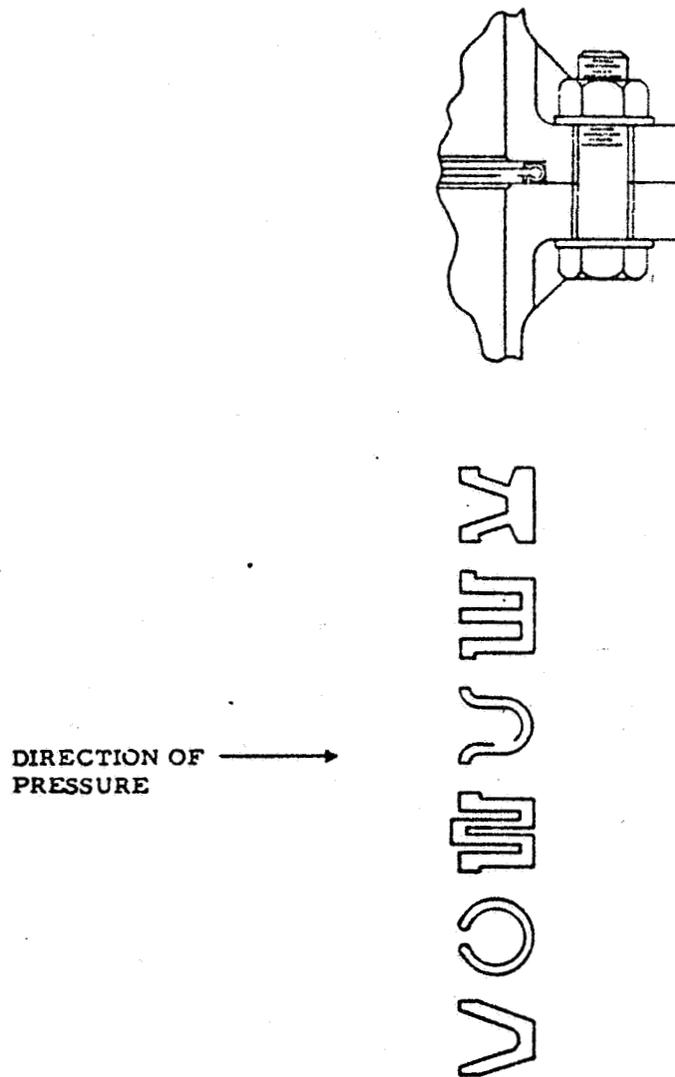
Resilient metal seals combine the efficiency of elastomeric O-rings with the extended temperature capability of metal gaskets. The basic structural element is usually a high-strength metal, and a soft coating of metal or plastic provides the actual sealing. Like O-rings, these seals are self-energizing, have small cross sections, require light closing forces, are often reusable, and have indefinite life. Common cross sections are shown in Figure 4.4-1.

Metal seals are sometimes used to replace O-rings to extend the temperature capability of a system or device.

4.4.1 Resilient Metal Seals

Most resilient metal seals incorporate the following characteristics:

- a. Low flange loading
- b. High contact stress
- c. Moderate to high springback
- d. Soft coating
- e. Pressure compensation



[24]
FIGURE 4.4-1 TYPICAL RESILIENT METAL SEAL CROSS SECTIONS

[30] Table 4.5-1 Hi-Pressure/Hi-Temperature Metal Flange Seal Source List

<u>Manufacturer</u>	<u>Location</u>	<u>Type of Seal</u>
Advanced Products, Inc.	North Haven, Conn.	V-rings and O-rings
Del Manufacturing Co.	El Segundo, Calif.	V-rings
Harrison Manufacturing Co.	Burbank, Calif.	K-rings
Haskell Engineering	Glendale, Calif.	K-rings
Hi-Temp Rings, Inc.	El Segundo, Calif.	V-rings
Hydrodyne Corp.	Hollywood, Calif.	E-rings
Navan Products, Inc.	El Segundo, Calif.	V-rings
Parker Seal Co.	Culver City, Calif.	V-rings
Pressure Science, Inc.	Beltsville, Md.	C-rings and O-rings
Tetrofluor Inc.	Inglewood, Calif.	V-rings
United Aircraft Products	Dayton, Ohio	O-rings



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Note: Sources of metal flange seals are not necessarily limited to the above list.

A soft spring (low flange loading) with relatively high bearing stresses is achieved by minimizing contact width. Seals must take up as little space as possible in order to optimize overall connector design. Metal seals incorporating all of the above features are available for grooves as small as 0.030 inch deep by 0.050 inch wide.

4.5 CONCLUSIONS AND RECOMMENDATIONS

This investigation has produced some basic conclusions regarding utilization of flange seals for high pressure cryogenic applications. Resilient metal seals can be considered as the most promising for achieving seal integrity for these environments. A parallel loaded joint (Figure 4.1.1-1) with groove type seal installation (Figure 4.3.1-1) should provide the optimum joint configuration. The seal cross section and flange-cavity dimensions are not standardized and there are no performance or testing standards by which they can be compared or evaluated. However, seals can be evaluated by several methods:

- a. Select a proven seal based on prior knowledge of performance in a similar environment, or on the technical advice of a reputable seal manufacturer. With knowledge of environmental conditions, performance requirements, and a basic understanding of flanged connector mechanics, this approach is quick and least expensive. Table 4.5-1 provides a list of sources for selection of a seal configuration.
- b. Test one or more seal designs. When confidence in a seal's performance is not high, a test program is probably warranted to increase confidence in the performance of the seal.
- c. Design a new seal where a unique application or the lack of an adequate available design may call for a unique new seal design.

Recommendations for a flange seal configuration for the application considered in this investigation are:

- a. Parallel-loaded joint.
- b. Groove type gland design.
- c. Metal coated resilient metal seal.
- d. Test program to prove the adequacy of the design for the application.

5.0 HYDROGEN EMBRITTLEMENT OF TRANSDUCER METALS

Among the modern theories for hydrogen embrittlement of steels there are certain common features. One is that there must be a source of mobile hydrogen, either gas precipitated in voids or atomic hydrogen in solid solution. Another is that stress and stress concentrations in the material aid the mechanism of the embrittlement process.



Hydrogen embrittlement has been classified into three types by researchers. These are: 1) hydrogen reaction embrittlement, 2) internal hydrogen embrittlement, and 3) hydrogen environment embrittlement.

5.1 HYDROGEN - REACTION EMBRITTLEMENT

This failure mechanism involves a form of chemical reaction between the hydrogen gas and the metal. For example, hydrogen reacting with oxygen in solid copper to form H_2O , or in steel carbon reacts with hydrogen to form methane. This type of reaction is prevalent in the petroleum industry and other chemical industries where the use of gaseous hydrogen at high temperature and pressure is required. This attack of the metal can be prevented by appropriate choice of steel containing carbide stabilizers. This particular mechanism is the least important as far as this report is concerned because of the high temperature and pressure conditions.

5.2 INTERNAL HYDROGEN EMBRITTLEMENT

This problem is primarily identified with steels but not limited to them. Almost all of the internal hydrogen found in steel can be traced to the steelmaking process. Part of the hydrogen in the melt will be trapped during solidification in the ingot and significant amounts may be retained in heavy sections. By virtue of improved steelmaking processes and welding techniques, particularly for susceptible grades of steel, this origin of hydrogen has been virtually eliminated.

5.3 HYDROGEN ENVIRONMENT EMBRITTLEMENT

Hydrogen environment embrittlement is the third and most important type for the purposes of this report since it duplicates the transducer using condition. This type of embrittlement is associated with a decrease in strength of a metal or alloy during service in hydrogen (gas or liquid), generally at high pressure. It is an environmental effect and occurs only while the metal is in contact with hydrogen.

Within the group of metals susceptible to hydrogen environment embrittlement the degree of embrittlement is not predictable. Generally, the higher strength alloys can be more embrittled than lower strength alloys. Also, for a given alloy heat treating to a higher strength level results in a potentially greater degree of hydrogen environment embrittlement.

The first comprehensive report on this subject was by Walter and Chandler in February 1969 [1]. The authors established four categories of embrittlement upon exposure to hydrogen at 10,000 psi and room temperature. These categories are:

1. Extreme Embrittlement. High strength steels and nickel base alloys are in this category. In unnotched specimens, failure is initiated by one surface crack which propagates into the specimen.

Table 5.3-1 [1] Results of Tests on Various Alloys
At Ambient Temperature in Hydrogen

<u>MATERIAL</u>	<u>PRESSURE</u>	<u>DEGREE OF BRITTLENESS</u>
18% NI (250) Maraging Steel	10,000 PSIG	Extreme
AISI Type 410 Stainless Steel		
AISI 1042 Quenched and Tempered		
17-7PH Stainless		
17-4PH Stainless*		
15-7 MO Stainless*		
H-11		
FE-9NI-4CO-0.2C		
Rene 41	10,000 PSIG	Extreme
Electroformed NI	7,000 PSIG	
AISI 4140	10,000 PSIG	
Inconel 718		
Inconel 718**		
NI-Span-C***		
AISI Type 440C Stainless Steel		
AISI Type 446 Stainless Steel ***	10,000 PSIG	Extreme
TI-6Al-4V (STA)	10,000 PSIG	Severe
AISI Type 430F Stainless Steel		
Nickel 270		
ASTM A-515 GR. 70		
HY-100		
ASTM A-372-IV		

Table 5.3-1 [1] Results of Tests on Various Alloys
At Ambient Temperature in Hydrogen (continued)

<u>MATERIAL</u>	<u>PRESSURE</u>	<u>DEGREE OF EMBRITTLEMENT</u>
TI-6AL-4V (Annealed)		Severe
AISI 1042 (Normalized)		
ASTM-A-517-F (T-1)		
ASTM A533-B		
HY-80		
AISI 1020		
TI-5AL-2.5SN ELI		
ARMCO Iron		Severe.
AISI Type 304L Stainless Steel		Slight
AISI Type 305 Stainless Steel		
BE-CU Alloy 25	10,000 PSIG	Slight
Titanium (Commercially pure)	10,000 PSIG	Slight
AISI Type 310 Stainless Steel		Negligible
A-286 Stainless Steel		
7075-T73 Aluminum		
6061-T6 Aluminum		
1100-0 Aluminum		
CEHC Copper		
AISI Type 316 Stainless Steel	10,000 PSIG	Negligible

*17-4PH Stainless and 15-7 MO Stainless are considered at least as susceptible to embrittlement as 17-7 PH stainless in this environment.

**Special tests performed by Rockwell for NP/SD showed no embrittlement problems on Inconel 718 at -260 F and 800 PSIG hydrogen [34].

***Type 446 Stainless is considered at least as susceptible to embrittlement as type 440C stainless in this environment.

****Predicted position of this alloy at this pressure.



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2. Severe Embrittlement. This category contains the largest number of metals tested including ductile, low-strength steels, pure nickel, and titanium alloys. Embrittlement is characterized by a considerable reduction of notch strength but no reduction of strength of unnotched specimens.
3. Slight Embrittlement. The metastable (tend to transform to martensite during deformation) type 300 stainless steels, beryllium-copper, and commercially pure titanium are in this category. Embrittlement is characterized by a small decrease in notch strength and notched ductility.
4. Negligible Embrittlement. Aluminum alloys, stable austenitic stainless steels and copper are in this category. These materials were essentially unembrittled and no surface cracks were observed.

It should be noted that all of the information obtained in categorizing these various metals was relative to high pressure (10,000 psi) testing. Some embrittling phenomena have been discovered at atmospheric pressure, such as in 4130 steel, but the testing done in this range is extremely limited.

Table 5.3-1 lists the results from testing various metals at 10,000 psig (except as noted).

5.4 PREVENTIVE MEASURES

Protective coatings and the addition of inhibitors are two basic preventive measures which can be taken to reduce the probability of hydrogen embrittlement in metals. Since the mechanism involves permeation of the surface of a metal or alloy, there are certain coatings of oxides and carbides that can reduce the hydrogen permeability. The following materials are listed in order of lowest permeability to highest permeability: aluminum oxide, tungsten, gold, various glasses, tungsten and molybdenum, nickel aluminate, aluminum solaramic enamel, copper, platinum, and nickel. Complete adherence to the metal is essential to forming effective hydrogen barriers.

Some investigators have observed that the degree of hydrogen environment embrittlement is reduced when impurities are present in the hydrogen environment. Impurities such as air, nitrogen, oxygen and argon were tested for embrittlement inhibiting capability by Hoffman and Pauls [32].

Their results showed that the addition of argon and purified nitrogen did not reduce embrittlement. It was suggested that the oxygen content was a factor in reduction of embrittlement. In their test on CK 22 (a 22 percent carbon, plain carbon steel) in 1470 psia hydrogen, an oxygen content of 1 percent completely eliminated embrittlement.

This impurity factor appears to be of least significance in embrittlement of high strength steels. Sawiki and Johnson [31] found that embrittlement of



high strength steels by hydrogen at atmospheric pressure is not influenced by oxygen contents of less than 200 ppm. They concluded that the inhibiting influence of oxygen is a function of its absolute partial pressure regardless of the total pressure of the system.

There are four types of cleaning processes which are generally considered to be low hydrogen embrittling or non-hydrogen embrittling. They are: mechanical cleaning, anodic cleaning, alkaline cleaning, and pickling in inhibited acids.

The surface roughness of a metal can also influence susceptibility to embrittlement. In general, rough surfaces enhance embrittlement. Chem milling, for instance, produces a surface which is more susceptible to embrittlement. Ketcham [33] recommends that all high strength steels over Rc10 be baked after chem milling. This is effective in recovering ductility if there is no surface barrier such as plating.

5.5 TECHNICAL DISCUSSION

The testing that has been done to date concerning hydrogen environment embrittlement has included many different alloys and metals. However, the various conditions under which these tests have taken place have been quite limited. The most significant testing has been done at room temperature and at 10,000 psi pressure. Ideally, a classification of materials as to degree of embrittlement would include various temperature and pressure ranges. However, this data is not available except for a few alloys. Few have been tested at pressures other than 10,000 psi and most of these at room temperature. It can be safely assumed that any material subjected to a lower pressure and/or temperature would be embrittled to a lesser degree than at the higher pressure and/or temperature. However, in the extreme embrittlement category, it cannot be predicted how much change in pressure and/or temperature it would take to significantly reduce the degree of embrittlement.

Stress level is an important parameter in predicting the degree of embrittlement in a metal. There is some indication that stress levels below the yield point of a material are very unlikely to be associated with embrittlement type failures.

Hydrogen embrittlement should not occur if one can truly design so that there is no material yielding and the design is based on the yield strength rather than on the ultimate strength of the material.

5.6 CONCLUSIONS

Generally based on the facts above it is concluded that pressure transducer materials are not considered a problem from hydrogen embrittlement susceptibility. The basis for this conclusion is that the diaphragm which is the most vulnerable component is designed for stress levels well below the yield point of the metal to obtain optimum performance with respect to linearity and repeatability. In addition, liquid hydrogen systems associated with space vehicles usually operate at 100 psia or less, thus are well below the high pressure levels known to contribute to the susceptibility problem.

Operational temperatures are also in the liquid hydrogen range, thus are favorable from the embrittlement standpoint.

In view of the general trend to conduct tests at higher temperature and pressure values and because of the lack of conclusive data available on the subject, it is recommended that the final determination regarding the safe application of a specific material be based on test results.

6.0 THE EFFECT OF CLOSE COUPLED VERSUS REMOTE TRANSDUCER INSTALLATION ON PRESSURE MEASUREMENTS

The need to make a measurement in an adverse environment often leads to the decision to plumb to the sensing transducer. In this way the transducer can be protected from the hostile environment by installing it in a temperature controlled area. There are penalties, however, for such a compromise. In the case of measuring a gaseous pressure, frequency data as a function of line length, is lost. In a gas-liquid interface at cryogenic temperature, it can result in phase, frequency and amplitude distortion. A total distortion of the actual pressure signature is shown in Figure 6.0-1.

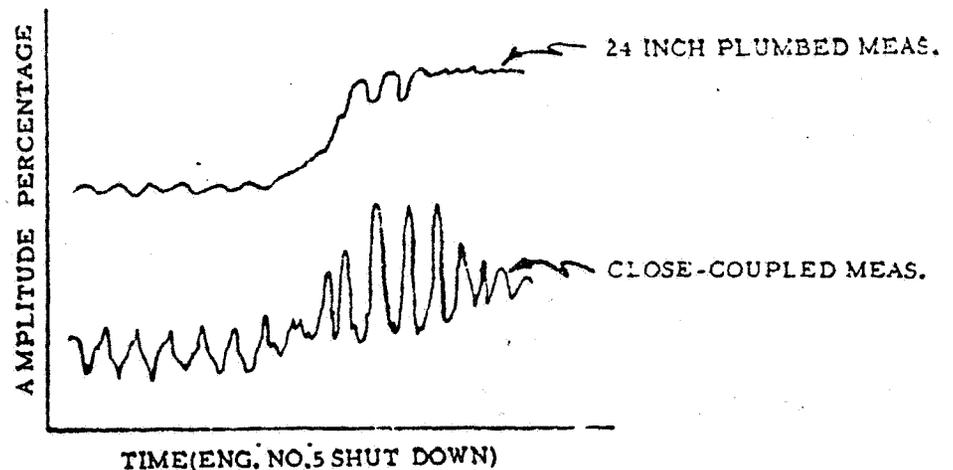


Figure 6.0-1 S-II Flight No. 7

In a gas measuring system only, the installation of a tube and transducer can be classified into two types, the "organ" pipe [36] and the Helmholtz resonator [35]. The former consists of a simple tube with minor variations in diameter, one end of which is open while the other is attached to a transducer cavity. The relative volume of the tube is large compared with that of the transducer cavity. The latter variation, the Helmholtz resonator, has a small tube volume compared to a relatively large cavity volume.



Let us assume a transducer cavity volume which is small relative to the line length that connects it to the transducer. The fundamental (fd) or organ pipe formula is equal to C/4L, the velocity of sound (C) divided by four times the length (4L). If the media being measured is Helium gas and the tube length is 5-1/4 inches, then:

$$fd = C/4L$$

$$\text{where } C = 15,000 / \sqrt{d}$$

$$d = \text{density at } 70 \text{ F}$$

$$\text{and } fd = 15,000 / 4L \sqrt{d} = 15,000 / 4(5.25) .407 = 1750 \text{ Hz.}$$

If we had used a 52.5 inch line, this value would drop to 175 Hz. The Helmholtz formula would apply where the volume of the connecting line was small relative to the transducers pressure cavity. Again, using Helium gas at 70 F we get a fundamental frequency (fd) as follows:

$$\text{(Helmholtz) } fd = \frac{C}{2} \pi \sqrt{\frac{\pi r^2}{L'V}} \quad \text{where } 2r = \text{line diameter and } r = .079$$

$$L' = 1.7r + L = .134 + 5.25 = 5.384 \text{ inch}$$

$$C = 15,000 / \sqrt{d}$$

$$\sqrt{d} \quad \text{for Helium at } 70 \text{ F} = .407 \quad C = 36,800 \text{ in/sec. } V = \text{volume cavity}$$

$$\text{So: } fd = 36,800 / 6.28 \sqrt{3.14 (.079)^2 / 5.384(.091)}$$

$$\text{and } fd = 1072 \text{ Hz.}$$

Therefore, if we know the measuring systems dimensions, the temperature and the gas media frequency capability can be established. This is applicable to a gas measuring system only.

It becomes impossible to measure the output characteristics of a bi-phase cryogenic measurement in which high turbulent flow exists when the sensor (transducer) is plumbed from the point of interest. As little as two inches of 1/4 inch line can lead to a distorted pressure signal output in both wave shape and frequency. The key term in association between information distortion and the use of a plumbed transducer is turbulence. Rapid pressure changes or surges which produce pulsations in the entire system. If no surging exists, phase and frequency information appear to be transferrable over long line lengths, however, amplitude information is questionable because in use only the output data is available.

There are two events that occur during turbulent flow as a result of plumbing a measurement. Turbulence forces the cryogenic liquid down the 1/4 inch line where it proceeds to compress the gas media in the system. However, as the liquid under surge moves down the line, it expands due to the change in

temperature gradient along the lines length. Both the resulting change in momentum of the mass of liquid in motion and the volume change produce the overall distortion of the output.

In a series of tests run in support of the general Saturn Program, it was established that some of this distortion due to temperature gradient turbulence and line length was present even in lines as short as 2 inches. A four gallon stainless steel tank was fabricated with five standard 1/4 inch bosses and two special bosses located at the bottom and just above the bottom of the tank. A total of ten pressure transducers, all of the same type and approximate range (0-50, 65 and 75 psig), were used. Two of the transducers were flush mounted to the special bosses while the five 1/4 inch lines had a total of six transducers plumbed to them in varying lengths and configurations. Two measurements were made at the top or input portion of the tank; was put on the recorder tape while the other read out real time. The correlation between the two flush mounted units measuring the cryogenic liquid directly and the ullage gas measurement compared very well with only minor distortions. Those measurements plumbed to the test tank showed a distorted and general erratic output proportional to line length and dynamic pressure input with the 2 inch plumbed transducer the least effected as shown in Figure 6.0-2.

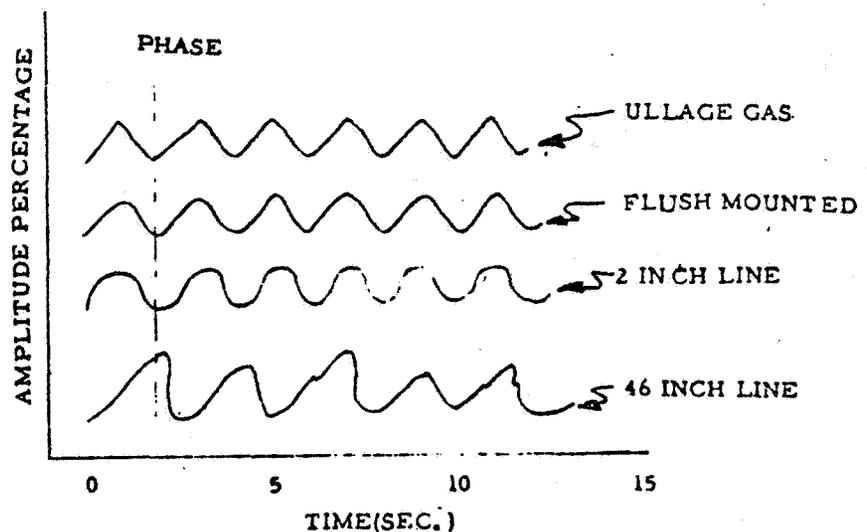


Figure 6.0-2 Lab Test Data

On the Saturn S-II Program, there were two measurements that graphically showed the line length bi-phase effect. One measurement was a high accuracy pressure transducer which contained an internally mounted proportional heater. It was located on a 1/4 inch stainless steel line 42 inches from a boss on the LOX pump inlet and was maintained at a relatively constant internal temperature.

Located on the same plane, 90 degrees from the measurements plumbed line, was another boss into which was directly installed a small light weight transducer. No line was involved as the 1/4 inch fitting on the transducer was screwed into and sealed against the boss. The transducer used for this measurement was light (4 oz.) and capable structurally of being mounted in a cantilever position. The original object of the plumbed measurement was to provide high accuracy steady state information which it did, however, as a result of the need to investigate the undamped oscillation phenomena noted in flight, it became apparent that another measurement was necessary in order that more information on frequency data could be obtained.

From the time of the addition of this new measurement, commencing with the S-II number seven vehicle, it became obvious that during transient periods, the two respective measurements did not read the same. Although the basic dc level seemed to remain the same, the perturbations or ac level changes were distorted on the plumbed transducer's output. Figure 6.0-3 shows a segment of data at two different times in the Saturn number seven flight.

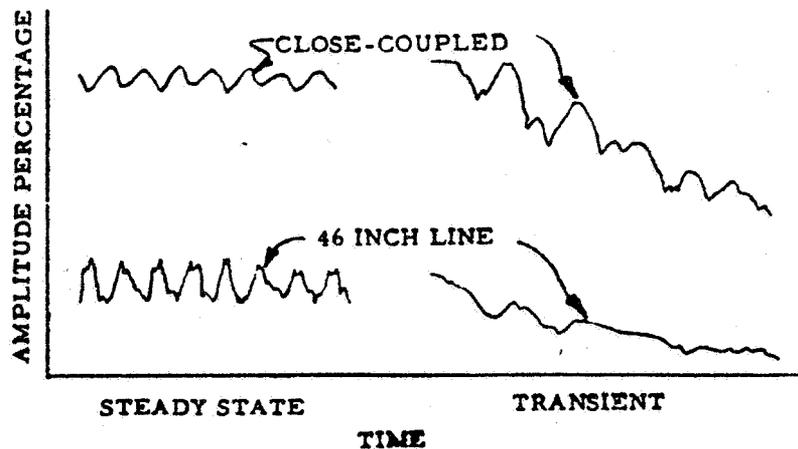


Figure 6.0-3 S-II-7 Flight Data

During the flight of the Saturn number eight, there was an emergency shutdown of engine No. 5. An undamped oscillation of increasing amplitude built up rapidly (< 5 sec.) until the engine turbo-pump cavitated and the pressure switches dropped out. This sudden shutdown produced a large surge of LOX down the 1/4 inch line of the 42 inch plumbed measurement. The results of this surge produced an output of the long lined measurement which lagged in output, shifted in phase, differed in frequency and was different in amplitude (less) than the close coupled transducer. Prior to the emergency shutdown, there was close correlation in frequency but not amplitude nor phase between the two measurements. (Figure 6.0-4).

This is an actual example of flight data verifying the laboratory test information.

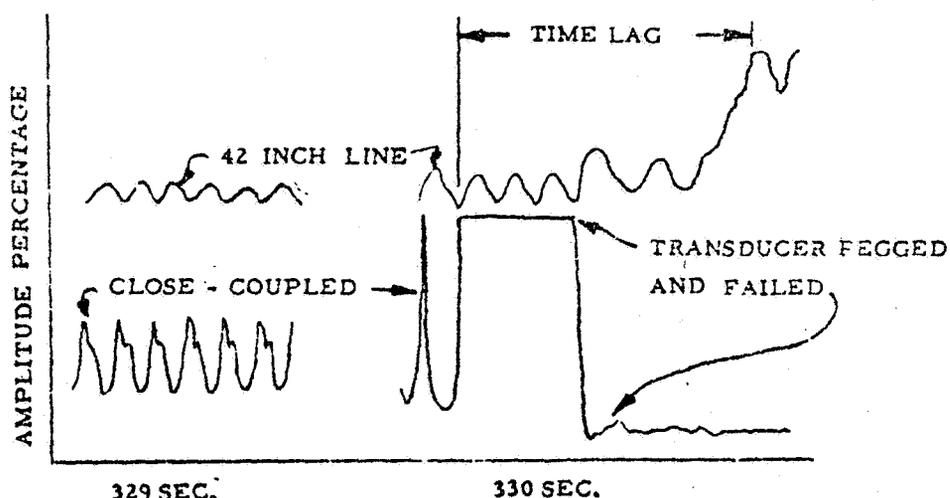


Figure 6.0-4 S-II-8 Flight Data

In making a liquid cryogenic bi-phase pressure measurement, there is no alternative to using a flush mounted transducer. Data obtained by using a plumbed transducer is not always valid. All that is needed is turbulence or line surging to completely distort all data information. At certain relatively quiet times, the data may appear believable.

The installation of a flush mounted measurement can also be achieved with relative ease if sufficient design planning is made prior to its implementation. The close coupled measurement was quite successful even though it was a modification using an existing installation. Had a boss been initially designed for it and a program of development been initiated as well as data handling techniques applied to it, both dc and ac data of high accuracy could have been provided.

7.0 TECHNIQUES IN TEMPERATURE COMPENSATION OF STRAIN GAGE PRESSURE TRANSDUCERS

Temperature compensation as applicable to strain gage pressure transducers usually means the classic use of compensating resistors and thermistors in the bridge circuitry of the strain gages. This report discusses this classic technique but in addition discusses additional provisions utilized on the Saturn S-II Program for compensation of a cryogenic pressure measurement transducer.



Strain gage pressure transducers exhibit an apparent pressure reading when subjected to temperature environments different than the temperature conditions under which the instrument was calibrated. This apparent pressure reading is a source of error which must be corrected where accuracy of the measurement is desired. In strain gage transducers temperature sensitivity is exhibited from two principle sources. The first is an error resulting from any transducer influence which alters the balance of the full bridge. This error source usually results from dimensional changes in structural members and resistivity changes in the strain gage elements. The second source results from a Young's Modulus coefficient in spring elements of the transducer. These include the diaphragm or other force summing member and springs and bending beams associated with the transducers construction.

Normally manufacturers employ both mechanical and electrical means for compensating these error sources. Mechanical designs usually consist of selecting transducer materials for compatible expansivity coefficients of critical sensor members. Other more complicated schemes involve mechanical compensation techniques such as in the use of bi metals in counteracting dimensional changes. Electrical compensation techniques involve the use of temperature sensitive resistors and thermistors in the bridge circuitry. In the case of zero shifts, resistors with positive temperature coefficients are installed into one or more of the bridge arms to compensate for the bridge unbalance which takes place with temperature changes. The sensitivity shift is compensated by adding thermistors to the input.

In order to best illustrate the above application the following example which occurred on the Saturn S-II program is presented. A pressure measurement made at a point on the feedline just above the LOX pump inlet of the No. 1 and 5, J-2 rocket engine required that phase, frequency and amplitude information at this point of installation be individually identified. The general installation and data requirements presented a worst case environmental situation in which the cryogenic fluid was flowing, at a high rate with turbulence. No installation method was available other than a 1/4 inch boss located on the LOX feed line so a small, light weight transducer was mounted in a cantilever position off the 1/4 inch boss. In this way the transducer diaphragm could be placed less than 2 inches from the flowing media and most of the frequency, phase and amplitude information could be measured. The two primary error sources in such an installation are: (1) torque sensitivity and (2) output shift due to temperature gradient across the transducer. Despite the careful use of the same torque value, within ± 5 inch pounds, for the calibration procedure and in the installations, errors due to torque ran -0.8 to -5.5% of full scale output. The temperature change due to temperature gradient across the transducer's length of 2 inches amounted to as much as 200 F, resulting in an error of +5 to +7% of full scale. The compensation for temperature in the case of this type transducers had been based on a constant temperature of -320 F and the compensation resistor network was so designed. The use here did not coincide with the calibration data. Compensation in this case consisted of knowing the installation parameters, referencing other measurements and previous system test data and finally, by using this data, to bias the output data during its reduction. Prior to actual use of the transducer, a series of data points were available as a result of various stage checkouts. Some were a single point check as in an ambient check with no

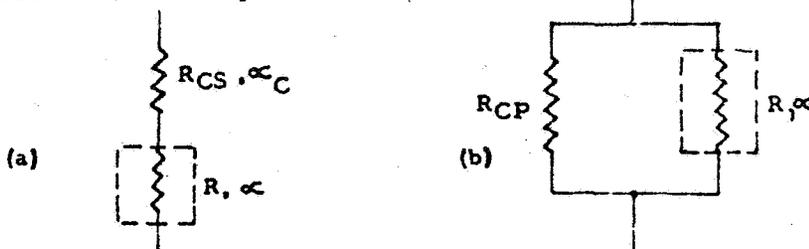
cryogenic in the tanks or in a pre-determined pressurization check. From this information, offset and torque sensitivity data was obtained and suitable corrections made to the calibration curve. Certain systems check-outs may provide additional slope change data which can be obtained from other systems such as a static type pressure measurement at or near the same location of the dynamic transducer installation. If a pressurization check-out of the tank is made the ullage data may be checked against the LOX pump data.

The previous problems illustrated some of the questions and solutions to a measurement not really planned for but one that was added as the results of the need to resolve a dynamic problem.

Starting with a similar requirement need to investigate, the following points, the (1) transducer design, (2) installation restraints, (3) calibration requirements and (4) the use of compensation resistors or thermistors. If instead of a 1/4 inch boss we had a 7/8 inch boss, a short flush diaphragmed pressure transducer could have been used. Since the transducer would have been close to being completely inserted into its boss most of the temperature gradient problem would have been solved and only torque would have been an error. Ideally, a pre-determined boss installation would completely accept a small flush mounted transducer. The transducer would have its resistor compensation network located physically as close as possible to the transducer diaphragm and its construction would be such that no strain would occur under torque. Two curves, one at ambient and one at -320 F could be taken in a simulated installation setup. The resulting error after all these considerations would probably be less than $\pm 1\%$.

Finally, temperature compensation in strain gage and strain gage transducer work is first concerned with "zero stability", the error produced by variation of ambient temperatures. Apart from this error there may be a temperature error in sensitivity (the slope of the calibration curve) which is mainly due to a thermal change of Young's modulus of the strained structure. This error may be important in strain-gage transducers employing springs, where it can be compensated by insertion of temperature-sensitive resistance in either side of the supply line to the transducer. The more difficult of the two is compensating for zero-instabilities. In order to eliminate the resistance variations at variable ambient temperatures of a piece of apparatus of resistance R , a compensation resistance in series, R_{CS} , or in parallel, R_{CP} , can be employed.

Let t be the ambient temperature,



at the apparatus and at the compensation resistance while t_0 is the reference temperature, normally +68 F. In the series circuit of Figure (a) the resistance increase ($R \propto (t-t_0)$) of the apparatus can be compensated by a resistance R_{CS} with a negative, i.e., opposing, temperature coefficients, $-\alpha_C$.

$$R \propto (t-t_0) = R_{CS} \alpha_C (t-t_0) \quad (1)$$

or

$$\frac{R_{CS}}{R} = \frac{\alpha}{\alpha_C} \quad (2a)$$

The parallel circuit (Figure b) yields for $\alpha (t-t_0) \ll 1$

$$\frac{R_{CP}}{R} = \frac{\alpha_C}{\alpha} \quad (2b)$$

The total resistance at room temperature are thus:

$$\text{Series circuit: } R \left(1 + \frac{\alpha}{\alpha_C} \right) \quad (3a)$$

$$\text{Parallel circuit: } \frac{R}{\left(1 + \frac{\alpha}{\alpha_C} \right)} \quad (3b)$$

It is seen that in both cases, the ratio α/α_C should be as small as possible to avoid undesirable deviation from the nominal apparatus resistance R . This will be achieved by compensating resistances with negative temperature coefficients α_C as large as possible. Only certain semi-conductive materials (thermistors) conform to this requirement. They are strongly non-linear with temperature and are thus applicable only over limited temperature ranges. In practical circuits compensating resistance with small positive or negligible temperature coefficients are often preferred, in spite of their theoretical inefficiency, because of their linearity over a wide temperature range. In this case, full compensation cannot be achieved but with the appropriate choice of the resistance ratio R_{CS}/R , the fractional error at a temperature t can be reduced to any desired value, e . The series circuit (Figure a) yields

$$e \ll \frac{R \alpha + R_{CS} \alpha_C (t-t_0)}{R + R_{CS}} \quad (4)$$

or

$$\frac{R_{CS}}{R} \gg \frac{\alpha (t-t_0) - e}{e - \alpha_C (t-t_0)} \quad (4a)$$



No compensation is required when $\alpha(t-t_0) \leq e$. For larger values of $\alpha(t-t_0)$, the necessary minimum series resistance R_{CS} is obtained from equation (4a). (At negative values of α_C and $e = 0$, equation (4a) turns into equation (2a)). If the temperature coefficient α_C of the compensating resistance is negligible, equation (4a) becomes:

$$\frac{R_{CS}}{R} \gg \frac{\alpha(t-t_0) - e}{e} \quad (5a)$$

Similarly in the parallel circuit of Figure (b) we have:

$$\frac{R_{CP}}{R} \leq \frac{[e - \alpha_C(t-t_0)] [1 + \alpha(t-t_0)]}{[\alpha(t-t_0) - e] [1 + \alpha_C(t-t_0)]} \quad (4b)$$

which, for small resistance changes, simplifies to:

$$\frac{R_{CP}}{R} \leq \frac{e - \alpha_C(t-t_0)}{\alpha(t-t_0) - e} \quad (4c)$$

Compensation is not required for $\alpha(t-t_0) \leq e$. At large temperature variations the maximum value of R_{CP} can be obtained from equations (4b) or (4c). (With negative values of α_C and $e = 0$, equation (4c) becomes equation (2b)). If the temperature coefficient α_C of the compensating resistance is negligible equation (4c) becomes:

$$\frac{R_{CP}}{R} \leq \frac{e}{(t-t_0) - e} \quad (5b)$$

In conclusion the optimum accuracy for a strain gage pressure transducer measurement can be achieved if all the above noted techniques are applied. The complete compensation of the measurement must start with the understanding of the design requirement and carry through the final calibration update just prior to use. In between the design and the final calibration, the sensor construction must be coordinated with the installation requirement, compensated for temperature changes by using resistors or thermistors and initially calibrated. If all of the above are adhered to a nominal 5% of full scale transducer can be made to give an output close to 1% of reality.

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